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Human and Community Response to Impulse Noise A Literature Review

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**HUMAN AND COMMUNITY RESPONSE
TO IMPULSE NOISE:
A LITERATURE REVIEW**

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HUMAN AND COMMUNITY RESPONSE
TO IMPULSE NOISE; A LITERATURE REVIEW

by

Paul D. Schomer

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ABSTRACT

The purpose of this study is to provide a basis in which one can examine open pit mining noise. This study reviews 47 pages on human response to impulse noise and includes virtually every paper in the open literature dealing with either annoyance or community response. Most of the papers come from the mid-1960's through the mid-1970's and deal with sonic boom noise. However, sufficient data are found to understand and to treat all impulse noise including sonic boom, military blasts (artillery, armor, etc.), and open-pit mining blasts in a common fashion. This understanding of impulse noise can be used to assess the effects of open pit mining operations on people and communities.

CONTENTS

1.0	<u>Introduction</u>	Page
1.1	Background	1
1.2	Types of Studies	2
1.3	Purpose/Approach	4
2.0	<u>Summary of Impulse Noise Studies</u>	
2.1	Introduction	6
2.3	Laboratory Tests of the Noisiness and/or Annoyance of Transient Signals	14
2.4	Tests Including Vibration as a Stimulus	24
2.5	Attitudinal Surveys - Boom Effects	42
2.6	Studies Relating to Noise from Explosives	54
2.7	Summary Reports, Physiological Damage and Reading Guide	62
3.0	<u>Response to Impulse Noise</u>	
3.0	Introduction	64
3.1	What type of noise measure is best for predicting human response to impulse noise?	64
3.2	When people respond indoors to a blast or boom stimulus, do they respond to the noise, the noise-induced vibration, or both?	65
3.3	Can sonic boom data be used to infer response to open-pit mining noise, and can blast data be used to infer response to sonic boom noise?	66

3.4	What characterizes people who complain about impulse noise?	68
3.5	Is annoyance and are complaints related to the average impulse amplitudes and their frequency of occurrence, or to the fewer very loud impulses?	69
3.6	Do people accommodate or grow used to impulse noise?	69
3.7	For community response, what is more important: the response of people outdoors or indoors?	70
3.8	Are there any adverse physiological effects expected from open-pit mining noise at the levels normally encountered in the community?	71
3.9	Does open-pit mining noise have an effect on livestock?	71
References		72
Appendix A		76
Appendix B		87
Appendix C		89

CHAPTER 1

INTRODUCTION

1.1 Background

It is generally accepted that for many steady sounds the loudness level, or loudness as judged by human observers, can successfully be predicted from measurements with relatively uncomplicated instruments. Prediction of the loudness of impulsive sounds is not as simple. In many cases, however, the most important attribute of the noise is the annoyance or nuisance caused by the noise, and not its loudness or loudness level.

"Loudness", as used herein, is a human judgment as to the intrinsic magnitude of the sound. In contrast to loudness, the concept of annoyance is characterized by terms such as noisy, annoying, and bothersome. This latter concept is thought to include a judgment about the source itself as well as its judged loudness. For example, a concert orchestra's passage may be loud but not annoying whereas a truck or plane may be not as loud, but quite annoying. Also, such factors as pure-tones (the compressor whine of a landing jet plane) may make sounds more annoying while doing little to increase their judged loudness. Both of the above terms, "loudness" and "annoyance", are considered to result from human judgments. In contrast, meter readings are characterized by the "amplitude" of the sound pressure or the sound pressure level.

Even for steady noises, general prediction of the annoyance or nuisance is a very difficult problem, involving not only acoustical and physiological parameters, but also psychological and sociological factors, many of which are inadequately known. For impulsive sounds, the agreements

between the results of objective measurements and subjective evaluations is usually less satisfactory than for steady sounds.

Overall human response to impulsive sounds is exceedingly complex and involves not only the physical stimulus, but also the immediate environment, the ambient noise conditions, the experience, attitudes, and opinions of those exposed, as well as various factors not directly related to the stimulus (see Figure 1).

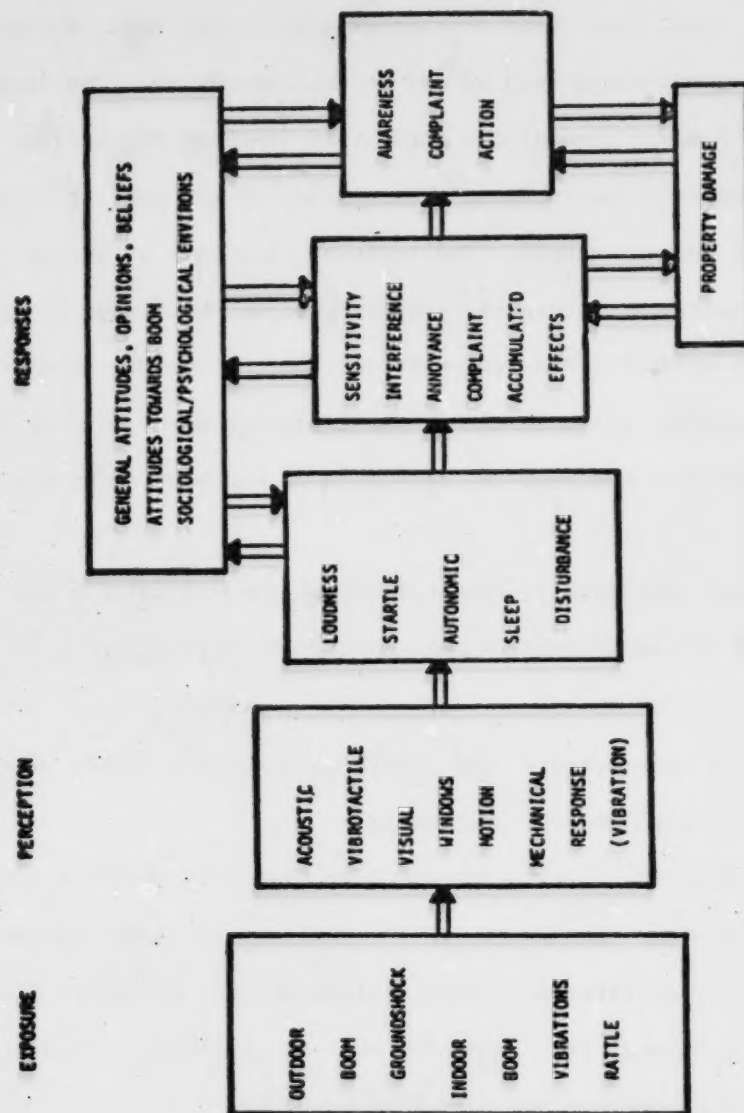
Since impulsive sounds are an important part of the general acoustic environment, much research aimed at elucidating the basic properties of human hearing and human response to noise, and improving measuring methods has been performed.

1.2 Types of Studies

Studies and experimental investigations can be roughly divided into five categories or types. These are:

1. Laboratory tests of loudness using artificially generated sounds.
2. Laboratory tests of annoyance using artificially generated sounds.
3. Laboratory tests of loudness or annoyance using real sounds or recordings of real sounds.
4. Field tests of loudness or annoyance using closely controlled sources as stimuli (e.g., explosive charges of fixed size at a fixed distance, or supersonic aircraft at a fixed altitude, position, and speed, etc.).
5. Community noise surveys or public opinion samples. In contrast

Figure 1 (from Von Gierke, ref. 41) Man's individual and group reactions to sonic booms



to the four types of tests above, the stimuli for these surveys are usually considered to be uncontrolled.

The first four types of studies require the human subject to make a judgment about each of the stimuli presented. The judgment may be in the form of a magnitude estimation in which the subject estimates the magnitude of the loudness or annoyance of the test stimulus as compared to a control signal. The judgments may also be in the form of paired comparisons, where the subject chooses the louder or more annoying of two stimuli. The judgments can combine the two, requiring that the subject not only choose the louder or more annoying of two stimuli but also estimate the magnitude of one with reference to the other.

By way of contrast, community noise surveys solicit the respondent's opinion of the noise environment and his ability to cope with it. Factors thought to contribute to annoyance such as startle, speech interference, and activity interference, are probed along with a series of factors found to correlate with annoyance responses.

These survey results characterize community response to the noise environment since they represent the opinions of people subjected to the noise(s) over an extended period of time (weeks, months or years). Control results are formed from responses taken in unaffected areas or from responses taken before the period of exposure.

1.3 Purpose/Approach

The purpose of this study is to review, summarize and explain the major research dealing with the effects of impulse noise on people and

communities. The primary goal is to provide a research basis in which one can examine open pit mining noise. Studies of sonic boom, artillery and demolition, and laboratory tests using artificial transients are the only types of studies available to provide this basis.

All available references dealing with human annoyance to single impulsive sounds have been utilized in the development of the material in this report. In all, forty-seven references were consulted. Of these, twenty-nine represented original studies and have been dealt with in some depth in the text.

The main text of this report is divided into three chapters. Chapter 2 summarizes various relevant studies, tests and papers. The original abstract or summary is given and, as appropriate, other parts of the paper are quoted.

Chapter 3 examines the key issues relating to human and community response to open pit mining noise. Questions are posed and answers are given (pro, con and otherwise) based on the results found in this literature review.

For convenience, Appendix A provides a glossary and Appendix B crosslists the references by primary author and reference number.

CHAPTER 2

SUMMARY OF IMPULSE NOISE STUDIES

2.1 Introduction

Much basic research has been undertaken to develop measurement techniques appropriate to the transient character of impulsive signals. Fundamental to the development of such techniques is a clear theoretical understanding of human response to transient signals. For example, it is essential to understand the relationships between the physical parameters of transient signals and their effects on judgments of loudness or annoyance. Some parameters may have no measurable influence on the perceived loudness or annoyance of an impulsive signal, while others may play a large part in determining perception of these qualities.

Amplitude, spectrum and energy are the three parameters most often studied. (Some investigators have preferred to use the time-domain concepts of rise time and duration in place of the frequency-domain concept of spectrum.)

These topics are introduced in Section 2 of this chapter which contains a discussion dealing with laboratory tests for the judged loudness of impulsive noise. While perhaps not directly applicable to the purposes of this report (annoyance rather than loudness is the more important judgment needed to characterize human response to open pit mining noise), this material nevertheless does form a foundation for much of the human/community response research which follows. The casual reader may wish to skip this section.

Section 3 discusses laboratory studies dealing with the noisiness or annoyance of transient signals. These studies are characterized primarily

by artificially generated acoustical stimuli (sometimes simulating sonic booms). The stimuli do not contain significant energy below about 20 Hz and the people tested are not subjected to vibrational stimuli.

In section 4, studies are considered which explicitly include acoustically generated vibrational stimuli in addition to the acoustical stimuli. These studies include field tests where subjects in real structures respond to blasts or sonic booms and laboratory tests at the Stanford Research Institute (SRI) using a specially designed test chamber.

Attitudinal survey results for sonic booms are summarized in Section 5. Because people are responding to real booms, vibrational effects induced by the booms are implicitly included in the results.

Section 6 deals with studies relating to noise from explosives and section 7 deals with such additional information as other summary reports, physiological damage and a reading guide to the cited literature.

Figure 2 illustrates the range of years spanned by the literature in the various sections. As can be seen, the tests which explicitly include vibration generally come after the tests which do not. All sonic boom research ends in 1972 with the decision to not allow sonic booms over land.

2.2 Loudness of Transient Signals

Traditionally, the unit of measurement for the loudness of steady continuous noises has been power, or energy per unit time. It is im-

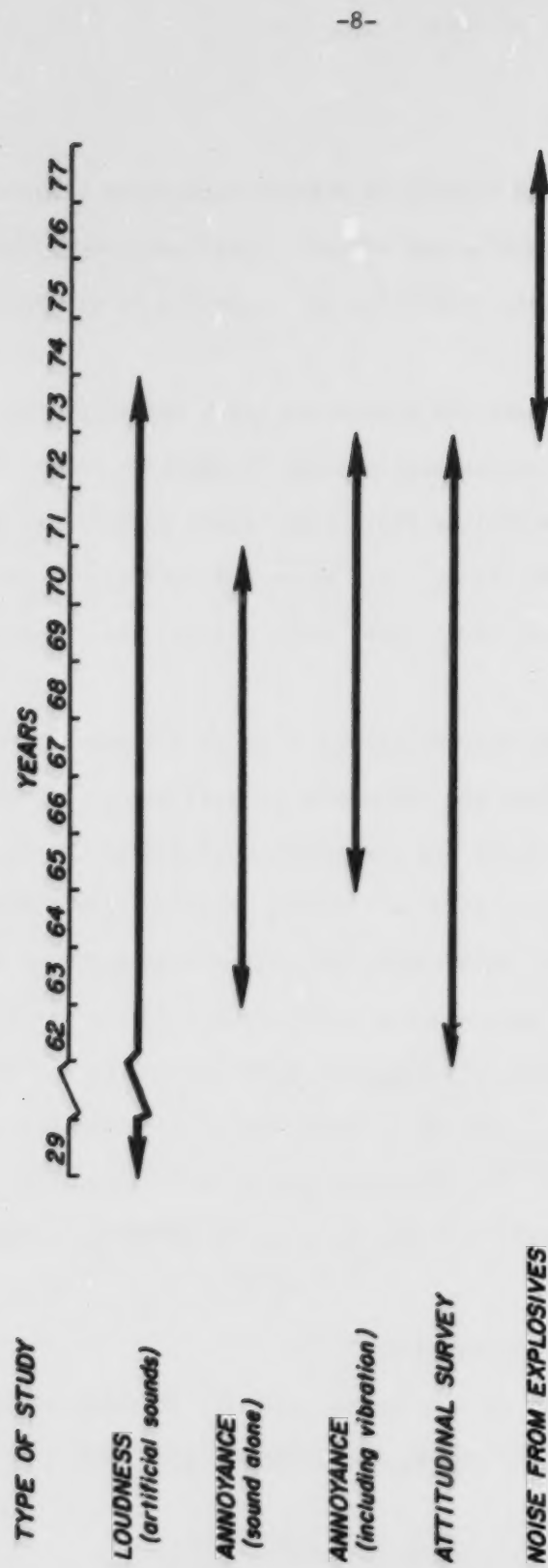


FIGURE 2 TIME SPAN OF MAJOR STUDIES CITED BY TYPE OF STUDY

plicitly assumed in the measurement of steady noises that signal duration has no substantial effect upon its subjective loudness level. (I.e., the judged loudness of a machine is the same if it runs for one minute or ten minutes.) Impulse noises, however, are sufficiently short, so that their duration has a substantial effect on their judged loudness. (I.e., whether a noise burst is present for 1 msec or 10 msec effects the judgment of its loudness.) The current theory of acoustic researchers is that the way to account for the perceived loudness of an impulsive sound is to assume that the ear integrates the acoustic power of the impulse over a finite duration. This period of integration (in seconds) is called the time constant of the ear. Roughly speaking, sounds which are shorter than this time must be integrated and those which are longer in duration must be merely averaged in order to correlate with judged loudness. To find the apparent loudness of an impulse, one calculates the acoustic energy of the impulse, finds the effective (average) sound pressure level by dividing this energy by the time constant of the ear, and proceeds as though the sound were steady or continuous.

The assumption of a finite integration time allows treatment of both impulsive and continuous sounds within a common framework. Crucial to this approach is accurate knowledge of the ear's time constant. Unfortunately, there is remarkably little agreement among researchers about this value.

Following pioneering work by von Békésy⁽¹⁾ in 1929 on the effects of duration on perceived loudness of tones, Garner⁽²⁾, and Miller⁽³⁾, and Munson⁽⁴⁾ laid the groundwork for subsequent studies. Typical of the

variation, von Békésy concluded that the time constant was about 180 msec, Munson found the time to be about 250 msec, and Miller estimated the time constant to be about 65 msec at all but the lowest sensation levels.

In some of the subsequent studies von Port⁽⁵⁾ estimates 70 msec while von Niese⁽⁶⁾, summarizing studies performed at Dresden, concludes that 25 msec is a good value and von Zwicker,⁽⁷⁾ reporting on studies at Stuttgart, estimates 100 msec as the time constant value.*

As a sample of this large body of literature, papers by Miller, Garrett⁽⁸⁾, von Reichardt and von Niese^(9, 10), and Boone⁽¹¹⁾ are presented.

George A. Miller (Psycho-Acoustic Laboratory, Harvard University, Cambridge, Massachusetts) "Perception of Short Bursts of Noise", Journal of the Acoustical Society of America, Volume 20, No. 2, 1948.⁽³⁾

Abstract

Short bursts of random (white) noise were used to study the perceptual growth and decay of the noise experience. Noise, unlike sinusoidal tones, does not change materially in spectrum as the duration of the sound is varied.

A short burst of noise must be more intense in order to be equal in effectiveness to a longer noise. Thus, the threshold of hearing is lowered by increasing the duration of the noise up to durations at least as long as one second. The loudness of an intense noise, however, depends upon its duration up to durations of only 65 msec. Judgments of the slowest rate of decay of a noise which sounded indistinguishable from an abrupt termination also led to the concept of a critical time of approximately 65 msec for the sensation to decay to threshold from any steady magnitude of stimulation.

From these data it is inferred that the auditory system acts as if the growth and decay periods of the noise perception

* These reported values represent averages. As is discussed later, there are large variations between subjects in virtually every experiment.

depend upon differences in latencies among the various neural paths in transmitting the cochlear activity to the higher centers of the brain. According to this hypothesis, the activity in the slowest pathways arrive at the higher center 65 msec after the activity of the fastest pathways. By means of this hypothesis it was possible to predict the judgments of time of termination of noises in the two ears when the intensity of the noise differed between the ears.

Discussion

Basically, Miller finds the time constant to be 65 msec at all but the lowest sound pressure levels. At low levels (below about 50 dB) he finds a longer time constant which increases with decreasing sound level and he hypothesizes two factors: (1) that the sound energy must build up before there is any transmission via the neural paths, and (2) that the neural paths themselves act as delayers, with the slowest ones exhibiting delays of up to 65 msec.

R. M. Garrett, (Vickers Research Ltd., Sunninghill, Berkshire, England), "Determination of the Loudness of Repeated Pulses of Noise", Journal of Sound and Vibration, Volume 2, 1965.⁽⁸⁾

Abstract

The loudness of repeated pulses of white noise has been compared, subjectively, with the loudness of a continuous white noise.

A procedure is proposed for calculating the equivalent level of the pulsed noise from a knowledge of the time-intensity characteristics.

The time-intensity characteristics can be determined either from oscillograph or by means of the meter proposed in outline at the end of this paper.

Discussion

The judgments required of the subject in all of these types of tests are apparently extremely difficult for an observer to make.

Practically every investigator of impulsive sounds has commented upon this aspect of the problem.

Garrett states, "Although the possible dependence of relative level and repetition frequency in overall level may explain some of the scatter, the major source of variation is the large difference between the responses given by different subjects. . . . These large inter-observer differences make the interquartile ranges large and the position of the medium can be readily influenced by fluctuations in subjects' performance. As an example of the possible influence of non-auditory stimuli, one subject was observed to make settings of up to 10 dB higher than normal in the month following her giving up smoking."

Only abstracts are included for the next three papers since these abstracts alone serve to illustrate the discussion surrounding determination of the time constant of the ear.

W. von Reichardt and H. von Niese (Technische Universität Dresden Sektion Information Technik, East Germany), "Choice of Sound Duration and Silent Intervals for Test and Comparison Signals in the Subjective Measurement of Loudness Level", Journal of the Acoustical Society of America, Volume 7, No. 4, 1970. ⁽⁹⁾

Abstract

To avoid faulty judgments when making subjective loudness-level measurements of noises, the time function of the 1000-Hz reference tone should be adjusted, as far as possible, to that of the test noise. For trains of repeated impulses, it should be arranged to have the same duration of impulse, the same duration of silence between them, the same repetition rate, and the two signal trains should be presented for the same length of time. For continuous noises, these signals should be presented with the same duration, in the range 250-500 msec and with silent intervals of 500-1000 msec. The loudness level of the 1000-Hz reference tone when presented in very short bursts is to be modified in accordance with the findings of this paper and these findings should be incorporated in the next issue of ISO recommendation 131.

W. Reichardt (Institut für Technische Akustik, Technische Universität Dresden, East Germany), "Subjective and Objective Measurement of the Loudness Level of Single and Repeated Impulses", Journal of the Acoustical Society of America, Volume 47, No. 6, 1970.⁽¹⁰⁾

Abstract

The subjective measurement of impulsive sounds involves equal duration for the 1-kHz comparison tones and the same repetition rate as the impulses being measured. The loudness levels of the short 1-kHz tones and repeated short 1-kHz tones can be taken from nomograms presented. The objective measurement of impulses requires an impulse sound-level meter with an RC-integrating network following the squaring device. The RC time constant must simulate the inertia of the human ear. The rise time and decay time constant must be the same. This impulse SLM indicated the same effective value as the classical sound-level meter for steady noises or for rapidly repeated impulses. The value indicated for slowly repeated impulses is higher, and we have a continuous transition to this higher value. The decay time constant must correspond to the rate of decrease in loudness after the sound has stopped. This can be described as $T=25$ msec or as 60-dB reverberation time of 0.35 sec. The reading of such an impulse sound-level meter with A weighting is designated L_{A1} . Loudness calculation by Niese's (1956 *Hochfrequenztech. u. Elektroajust.* 65,4.) method, for either single or repeated impulses, requires a spectrum correction L_{sp} to be taken from a nomogram, $L_{N1}=L_{A1}+L_{sp}$. Stevens' (1960 *Acustica* 10, 304) methods, for single impulses repeated less frequently than 2/sec, require the dynamic impulse level L_{C1} to be measured in 1-oct or 1/3-oct bands. Impulses repeated more frequently than 2/sec are measured and calculated in the classical way, but need by this method another impulse correction $L_1=L_{A1}-L_{as}$.

M. M. Boone (Department of Technical Physics, Technological University of Delft, the Netherlands), "Loudness Measurements on Pure Tone and Broadband Impulsive Sounds", Acustica, Volume 29, 1973.⁽¹¹⁾

Abstract

Niese describes the buildup of the loudness of impulsive (short duration) sounds with the aid of two assumptions: (1) the ear is a square law rectifier, (2) buildup is governed by a single time-constant.

There is a great deal of confusion in the literature as to the numerical value of this time constant: 23 to 200 msec have been suggested. Nevertheless a Draft Revision of the IEC

Recommendation 179 for an Impulse Sound Level Meter prescribes 35 msec.

Our own findings with about 20 test subjects go to show that this value is certainly too low. In addition it evolved that loudness matching of narrow- and wide-band signals yields an unacceptable spread between different test subjects.

Other parameters studied in addition to the time constant of the ear are intensity, rise time, spectrum, duration, and repetition rate. Typical are studies by Gustafsson⁽¹²⁾ and Carter⁽¹³⁾.

Results from these types of studies generally show a power function relation between amplitude or duration, and loudness. That is, the correlation between log (duration) or log (amplitude), and log (loudness) is large--typically .9 or greater.

Varying rise time changes the spectrum. As with continuous sounds, the ear is found to be most sensitive to the middle frequencies (500-4000 Hz).

Since annoyance rather than loudness is the more important judgment, this section dealing with loudness has been purposely kept brief and does not include all of the available literature. In the following sections which deal with annoyance every attempt has been made to be exhaustive with respect to the available literature.

2.2 Laboratory Tests of the Noisiness and/or Annoyance of Transient Signals

Fidell and Pearsons studied the noisiness of impulsive sounds rather than the loudness of impulsive sounds. They prepared two papers: one was a NASA contractor report entitled Study of the Audibility of Impulsive Sounds,⁽¹⁴⁾ and the other was a journal article based on that report entitled "The Noisiness of Impulsive Sounds"⁽¹⁵⁾. The abstract to the

journal article states:

Abstract

Experiments were performed in an anechoic chamber to investigate the effects of duration, intersignal interval, repetition, and frequency on the perceived noisiness of impulsive signals. All data were collected by an adaptive psychophysical procedure called Parameter Estimation by Sequential Testing (PEST). The major conclusions were that

- (1) the phase spectrum of an impulsive signal is irrelevant to its perceived noisiness, and
- (2) the ear's sensitivity to noisiness of impulsive signals resembles an energy summation process; i.e., it appears to integrate the total acoustical power of noise events to at least 100 seconds.

Discussion

In these experiments five basic transient wave forms were used to construct the test stimuli: (1) an ideal N-wave, (2) an N-wave with a 1 msec rise and decay, (3) a triangular wave, (4) a square wave, and (5) a doublet wave form. For each, four variant wave forms were generated by taking the Fourier transform, scrambling the phase and inverse transforming. Thus, any two members of a wave form family have distinctly different shapes but share nearly identical power spectra and duration (except for the doublet). Ten observers were used in this study.

In the duration experiment, ten observers judged filtered bands of white noise having durations ranging from 10 msec to 1 sec. These results coupled with results of a different test with durations ranging from 1 sec to 100 sec led to conclusion two above.*

* Wave form shapes are given in the glossary.

The two conclusions above are quite important to a study of human response to open pit mining noise. First, noisiness and annoyance are the issues when dealing with human or community response, not loudness; and since this work shows that the perception of noisiness involves an integration by the ear and/or mind of acoustic energy for at least 100 seconds, the entire issue of the ear's integration time as it relates to loudness is sidestepped. Secondly, the fact that the perception of the noisiness of a stimulus is dependent only on its spectrum, and not on its phase, means that an open pit mine blast noise and a sonic boom both having the same weighted spectrum will be judged alike on the basis of noisiness, even though their wave forms may appear quite different in the time domain due to phase differences. That is, although the shape may be different, if the spectrum and duration are the same then their judged noisiness values are the same.

Since Fidell's test signals included an ideal N-wave (sonic boom) and four phase-distorted versions of this ideal N-wave, and an N-wave with a finite rise time and four phased-distorted versions of it, blasts having the same spectrum and duration would be judged equal in noisiness to these N-waves.

Other important studies utilizing artificially generated sonic booms (N-waves) are the pioneering works by Broadbent and Robinson⁽¹⁶⁾ in 1963, Zepler and Hare⁽¹⁷⁾ in 1965, Pearsons and Kryter⁽¹⁸⁾ in 1965, and Shepherd and Sutherland⁽¹⁹⁾ in 1968.

E. E. Broadbent (Applied Psychology Research Unit, Medical Research, Cambridge, England), and D. W. Robinson (National Physical Laboratory, Teddington, Middlesex, England), "Subjective Measures of the Relative

Annoyance of Simulated Sonic Bangs and Aircraft Noise", Journal of Sound and Vibration, Volume 1, 1964.⁽¹⁶⁾

Abstract

Experiments were conducted on a total of seventy-nine subjects, in which they were asked to estimate the relative annoyance of the sound of a jet aircraft, a piston-engined aircraft, and sonic bangs, each of which was reproduced electronically at various levels. For the sonic bangs, a sound typical of that received inside a building was chosen.

The results are generally consistent with those of earlier experiments using different scaling techniques, and in the case of the jet and piston aircraft sound broadly support the method of calculating perceived noise levels. The increment necessary to double annoyance is about 13 PNdB. The rate of increase of annoyance with level is greater in the case of the sonic bangs, about 10 dB for doubling.

By relating the reproduced noise levels to their original values it is concluded, with some reservations due to experimental limitations, that the upper limit of acceptable sonic bangs (as heard in domestic interiors [inside residences]) is about 1.9 lb ft² initial pressure jump measured on the ground in the open. This figure is based on the value of 110 PNdB for conventional aircraft sounds.

Discussion

For these tests three sounds were used, reproduced through six loudspeakers in a small room. Two were recordings of the fly-over noise of a Boeing 707 jet and a Lockheed Super Constellation piston aircraft. The third was an actual indoor recording of a sonic boom. The reproduction system was lacking in low frequency response.

This study, as all others during this time period, lacks the vibrational factors of all subsequent studies. As will be seen, however, the results are quite consistent with other studies of this period and with the later, more sophisticated, studies which include the vibrational input. The equality between a 1.9 psf boom and 110 PNdB for conventional aircraft is quite consistent with results by Kryter and the community survey data by Borsky and others.

As with so many of the studies, the authors note, "There was a fairly wide range in terms of decibels between the lowest and highest levels of bang [sonic boom] which different individuals found equal in annoyance for a particular level of aircraft noise."

E. E. Zepler and J.R.P. Harel (Institute of Sound and Vibration Research, University of Southampton, Hampshire, England), "The Loudness of Sonic Booms and Other Impulsive Sounds", Journal of Sound and Vibration, Volume 2, 1965. (17)

Abstract

The paper describes briefly, in the first part, the problem posed and gives the reasons which led to the development of a pair of earphones. Experimental values of the subjective loudness of an N-wave are given as a function of its three parameters, namely, rise time, maximum pressure and total duration.

In the second part an attempt is made to explain the results in the light of Fourier analysis. Curves are drawn of $k[F(w)]^2$ where $F(w)$ is the Fourier transform of the impulsive signal and k is a weighting factor derived from the phon curves. The areas under the curves giving the weighted energies are compared with subjective loudness. Agreement between the two is good. It appears, hence, that the loudness of impulsive signals of short duration and similar frequency density function is proportional to the weighted energy. The conception of equivalent pitch of an impulsive signal is discussed.

Discussion

In this pioneering work, specially constructed earphones were used to present the stimuli to the subject. N-waves and 400 Hz tones were alternately applied as stimulus and control. Again, great variation was found from subject to subject. The author states:

"As to be expected, results differed considerably between different subjects, but individual subjects were usually consistent within a few dB when due care was taken concerning the fit of the earphones. As an example, in a test including 40 subjects, the average loudness assessed was 94 dB. At the extreme ends, there were two subjects judging the loudness as 77 and 103 dB respectively. On repetition, they arrived at practically the same results. Their hearing, in an audiological test, turned out to be normal."

The authors were particularly concerned with air leakage around the earphones and the effect this would have on the low frequency response required for a good N-wave. To test the sensitivity of the experiment to the low frequencies, the N-waves were presented to the subjects with all frequencies below a cut-off frequency filtered out. The cut-off frequencies used were 20 Hz, 40 Hz, 120 Hz, and 240 Hz. The effect of the 20 Hz filter on the shape of the N-wave was to turn it into two fairly short positive-going impulses characteristic of an artillery piece. The other filters had similar although not identical results. (Figure 3)

The effect of the filters on judged loudness was measured for N-waves with rise times of 1 msec and 3 msec respectively. Filtering out all energy below 20 Hz and 40 Hz had practically no effect in either case on the judged loudness, while filtering out all energy below 240 Hz caused a drop of about 5 dB.

These results are important when considering open pit mining noise, for they offer the first positive indication that judged human response is independent of the very low infrasonic energy of large amplitude impulsive noises.

The authors also show that they can take the Fourier transform of the N-wave signal, calculate relative loudness, and obtain a reasonable correlation between calculated relative loudness and subject responses.

Following-up on the above study were studies by Pearsons and Kryter⁽¹⁸⁾ and by Shepherd and Sutherland⁽¹⁹⁾. Their tests were designed to circumvent some of the experimental problems faced by field researchers using actual aircraft (these field tests are described later in this report, refs. 20, 21, 22).

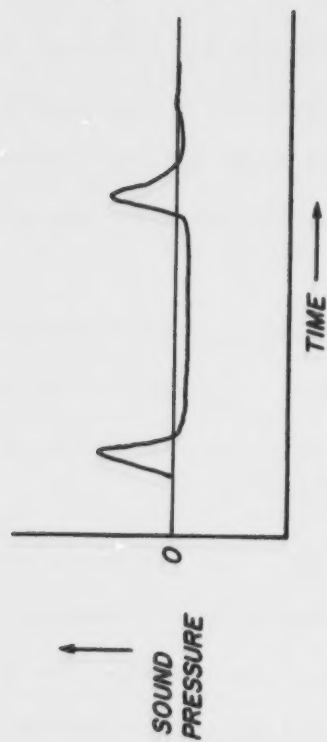


FIGURE 3 MEASURED PRESSURE PRODUCED BY
HEADPHONE AFTER HIGH-PASS FILTERING
OF SIGNAL.
(after Zepler and Harel, Ref. 17)

L. J. Shepherd and W. W. Sutherland, Relative Annoyance and Loudness of Various Simulated Sonic Boom Waveforms, NASA CR-1192, 1968.⁽¹⁹⁾

No abstract available

Discussion

Shepherd and Sutherland⁽¹⁹⁾ present a good background and history of work in the mid 1960's:

The first investigations concerned with the specification of human response were implemented with extensive flight test programs and yielded a large amount of useful data. Attempts to accurately define the nature of the pressure stimulus affecting large numbers of individuals was soon identified as an important problem area. The problems of variability in flight and atmospheric conditions were compounded by the problem of providing extensive arrays of instrumentation and the all important cost of providing enough supersonic flyovers for statistical reliability. Active confrontation with these problems lead to attempts to simulate the boom phenomenon in the controlled environment of the laboratory.

In order to implement tests of subjective reactions under laboratory conditions it is necessary to replicate as closely as possible the specific sonic boom pressure signatures. Zeppler and Harel (1965), enclosed only the ear in a headset-earmuff configuration and drove the reproducers with appropriate electrical waveforms. Kryter and Pearsons (1965), experimented with a 100 ft³ chamber with large loudspeakers mounted in the walls acting as pressure reproducers, and of the different techniques tried, the pressure chamber concept has provided the most accurate pressure time history sonic boom simulation.

In the summer of 1965, the Bioacoustics Laboratory at Lockheed developed a chamber similar to that described by Kryter and Pearsons, but differing in that the system utilized direct current amplifiers and servo system techniques to produce the required low frequency response.

Following the successful implementation of this facility, a series of test programs were designed and executed, in the interest of establishing the ameliorative effects of modifications in sonic boom parameters on human subjective response judgments. These studies were designed with a series of independent variables, including signature overpressure, duration, gross waveshape changes, and rise time. The results of these early Lockheed studies were reported at the June 1966 meeting of the Acoustical Society of America. The results indicated the existence of several important relationships between changes in the physical parameters of the sonic boom waveform and subjective human response, most notable signature rise time and overpressure were seen as response modifiers, parameters which had been thought to be important based on previous subjective studies and theoretical predictions. Several other

interesting effects were noted, including an apparent effect on subjective loudness appearing as a function of selective modification of the bow wave of the boom pressure signature. In addition, systematic examination using a number of differing experimental methods indicated possible differences to exist between loudness and annoyance as subjective judgment criteria.

As in earlier studies, these authors experimented with the effects of infrasonic energy on judged loudness and annoyance. Specifically, they experimented with N-waves of 3 different durations: 100 msec, 350 msec, and 500 msec. They state:

"Both loudness and annoyance are seen to be a function of rise time at any one particular duration. The variance is relatively constant for each of the three durations at any one rise time, which supports the finding that duration has little effect on judgments of loudness or annoyance. Spectral analysis indicates the greatest differences in the wave forms of 100, 350, and 500 msec duration to exist at frequencies generally below 10 Hz, with the fundamental frequencies seen to be a function of the duration of the signature. With the ear acting essentially as a high-pass filter network, these large subaudible spectral complements are of little apparent auditory significance and the potential for subjective differences becomes a function of the spectrum associated with the bow and tail waves and any summation effects thereof."

The authors also experimented with half N-waves. These can be thought of as approximating the leading part of a blast waveform. They included peaked N-waves, rounded half N-waves, and other variations. They found that these types of waveforms fit entirely within the framework established using the N-waves, and that their judged loudness and annoyance were predictable from knowledge of their spectral content.*

The authors concluded that, except for slow rising N-waves (10 msec rise time), there is no significant difference between judgments of loudness and judgments of annoyance for these N-waves and half-N-wave signals.

* Waveform shapes are given in the glossary.

With the slow-rising stimuli, the annoyance judgments are slightly above loudness judgments.

Karl S. Pearsons and Karl D. Kryter (Bolt, Beranek and Newman, Incorporated, Cambridge, Massachusetts) Laboratory Tests of Subjective Reactions to Sonic Booms, NASA Contractor Report 187, 1965.⁽¹⁸⁾

Abstract

Subjects compared, in a special laboratory chamber, the subjective acceptability or noisiness of sonic booms (simulated) that would be heard outdoors and indoors with the sound of subsonic jet aircraft and bands of filtered white noise. The subjective acceptability of the booms was expressed in terms of equivalent perceived noise level in PNdB. (The use of this procedure does not imply that a "PNdB" value can, or should, be calculated for a sonic boom; the PNdB value used refers to the calculated peak perceived noise level of the flyover sound of a subsonic jet aircraft that is judged to be subjectively as acceptable as a given sonic boom.) When heard indoors, a sonic boom having an outdoor overpressure of 2.3 psf was judged to be as acceptable as the sound of a subsonic jet heard indoors and having an outdoor level of 113 PNdB; the same boom heard outdoors was judged to be less noisy by an equivalent of 17 PNdB to the sound of subsonic jet at 113 PNdB. Some factors involved in estimating community response to airport noise are discussed.

Discussion

The work of Pearsons and Kryter using a specially designed chamber as discussed above was quite similar in design to the earlier study by Broadbent and Robinson.⁽¹⁶⁾ But in this new study, considerable effort was devoted to developing a room and instrumentation which would provide the high pressures, fast rise time and low frequency response necessary to reproduce a sonic boom. Five 18 inch center-tapped loudspeakers were utilized and driven by either a 75 watt McIntosh amplifier or a specially built D.C. power amplifier.

The chamber included a window which rattled and produced its own noise emissions when excited by the boom stimulus. Moreover, the recorded boom signature, as in the earlier test by Broadbent and Robinson, was made inside a real room responding to a real sonic boom stimulus. With this test the recordings were obtained inside a wooden framed building during supersonic aircraft flyovers. Thus, presumably, the recordings contain the secondary noise emissions of vibrating windows and objects within the rooms wherein the recordings were made.

Note first the agreement between the above findings and the earlier work by Broadbent and Robinson. A sound level of 2.3 psf is approximately 2 dB higher than a sound level of 1.9 psf, and so the equivalency of 113 PNdB found by Pearsons and Kryter compares most favorably with the equivalency of 110 dB found by Broadbent and Robinson. This result is most interesting in view of the special efforts taken by Pearsons and Kryter to ensure an adequate low frequency response and special window vibration within the test chamber. Secondly, we have the first indication of a response level shift between indoor and outdoor listeners. The result indicated is that for a given boom amplitude, the resulting annoyance is much greater indoors than outdoors.

2.3 Tests Including Vibration as a Stimulus

During the middle 1960's additional forms of experimentation and studies mushroomed worldwide. While the detailed laboratory studies by Shepherd and Sutherland quoted above were being performed, Kryter and Robinson independently moved their tests into the field for detailed paired comparison tests. In tests performed at Edwards Air Force Base, Kryter^(20,21) subjected persons, both indoors and outdoors, to aircraft flyovers and actual sonic booms. Almost simultaneously, in

England, Johnson and Robinson^(22,23) were exposing subjects, also both indoors and outdoors, to aircraft flyovers, sonic booms and simulated sonic booms using explosive charges.

In 1967, Kryter⁽²⁴⁾ constructed a special chamber which could be fitted out as a living room or bedroom and which presents the subject not only noise but also the vibration and rattle normally present during a sonic boom or other large amplitude impulse. Studies were performed in which subjects compared subsonic aircraft noise to simulated sonic booms⁽²⁵⁾ and others which recorded the effects of the simulated sonic booms on sleep.^(26,27,28)

In the early 1970's, most research on sonic boom effects ceased with the decision to prohibit supersonic flight over land in the United States.

All of the above studies, beginning with the Edwards AFB study and ending with Kryter's studies of sleep, are presented in order below. These studies all depart from other studies of the loudness or annoyance made prior to and during this period, in that they either use real or simulated stimuli, which present not only auditory signals to the subject but also true vibrational stimuli. In the field tests sonic booms and explosions shook the test houses, causing secondary vibrations, rattles and noise. In the laboratory studies the isolated room vibrated and the windows rattled as the simulated boom was presented to the subjects. Thus it can be expected that these studies measured not only the effects of the acoustic stimulus but in reality the entire summated effects of both the noise and its induced building vibration.

The following two tests, Kryter at Edwards Air Force Base, and Johnson and Robinson at an English air force base, are quite similar.

Both used subjects indoors and outdoors with sonic booms as the primary stimulus, and both used the flyover noise of subsonic aircraft as the primary comparison sound. In addition, Johnson and Robinson included explosives to simulate booms, and also bursts of white noise to test the subjects against a classical source.

The Edwards Air Force Base study by Kryter is massive. The references cited here include the interim report on "Sonic Boom Experiments at Edwards Air Force Base", dated July 28, 1966,⁽²⁰⁾ and the final report on "Psychological Experiments on Sonic Booms Conducted at Edwards Air Force Base", dated August 1968.⁽²¹⁾ The interim report deals not only with the psychological experiments but with the entire test which includes:

- (1) Introduction by K. D. Kryter
- (2) Summary of Rationale, Procedure, and Results to Date by K. D. Kryter and D. R. Grine, Stanford Research Institute
- (3) Annex A--Test Plan for Sonic Boom Experiments at Edwards Air Force Base assembled by Stanford Research Institute
- (4) Annex B--Psychological Experiments on Sonic Booms by K. D. Kryter, P. J. Johnson and J. R. Young, Stanford Research Institute
- (5) Annex C--Measurements of Sonic Boom in Four Parts by NASA, Langley Research Center, and by Stanford Research Institute
- (6) Annex D--Meteorological Investigations by C. Roberts et al., U.S. Department of Commerce, Environmental Science Services Administration
- (7) Annex F--Seismic Effects of Sonic Booms by J. C. Cook and T. Goforth

- (8) Annex F--Energy Spectral Density of Some Sonic Booms by
J. R. Young et al., Stanford Research Institute
- (9) Annex G--Response of Structures to Sonic Booms in two
parts with Part I by J. A. Blume of Blume & Associates
Research Division, and Part II by NASA, Langley Research
Center
- (10) Annex H--Response of Farm Animals to Sonic Booms by R.B.
Cassidy and R.P. Lehman, U.S. Department of Agriculture,
Animal Husbandry Research Division

To better understand this comprehensive program most of the text
of the introduction from the interim report is reproduced below.

SONIC BOOM EXPERIMENTS AT EDWARDS AIR FORCE BASE

INTERIM REPORT

I INTRODUCTION

A major question in the development of the SST has been the anticipated public reaction to the sonic boom. To help obtain resolution of this question, the Office of Science and Technology (OST) was requested in the fall of 1965 to develop a program of research on the effects of sonic booms on people, animals, and structures that would supplement and complement previous and on-going studies related to this problem. For this purpose the OST established a coordinating Committee on Sonic Boom Studies.

By agreement between the President's Science Advisor and the Chairman of the President's Advisory Committee on Supersonic Transport (PAC/SST), the Secretary of Defense designated the USAF as the OST Committee's implementation agency and program manager. The National Sonic Boom Evaluation Office (NSBEO) was established in the Directorate of Science and Technology Headquarters, USAF, to implement and manage those research studies approved and recommended by the OST. Stanford Research Institute (SRI) was selected to provide technical assistance for the definition of research problems and the analysis of research findings.

In January 1966 the OST Committee approved a series of experiments to be conducted at Edwards Air Force Base. The general objectives of these experiments were as follows:

1. To measure the judgments of the relative acceptability of sonic booms and noise of various intensities from various types of aircraft. The judgments were to be made by human observers situated both outdoors and in houses.
2. To determine the response of "typical" house structures to sonic booms having different signature characteristics.
3. To obtain detailed measures of sonic boom signatures in time and space as functions of the type of aircraft and mode of operation, and the atmosphere and ground through which the wave was propagated.
4. To observe the response of animals to the sonic boom.

Figure 1 (figure 4 of this report) is a chart of the organizations involved in the development and conduct of the Edwards experiments.

The following quotation summarizes the rationale for the psychological experiments. It is followed by a quotation from the findings of the psychological experiments as contained in the final report.

SUMMARY OF RATIONALE, PROCEDURES FOR THE PSYCHOLOGICAL EXPERIMENTS

The psychological studies were designed with the following conditions and assumptions in mind:

1. Subjects should be located both outdoors and in houses that would be "typical" for midwest USA, 1975, this being the area of the country that would most likely be exposed to sonic booms from proposed transcontinental SSTs.
2. Subjects would be adult males and females (the majority being housewives), and several hundred such subjects would be used.
3. The primary judgments to be made would be "relative" judgments of the acceptability of one sonic boom versus another sonic boom or of a sonic boom versus the noise from a subsonic aircraft. The rationale was that relative judgments allow the measurement of the effects upon listeners of variations in the physical characteristics of the sound, such as a sonic boom, to those effects of a second sound, such as the noise from a subsonic aircraft. The results would presumably provide: (1) a "calibration" of human response in terms of different sonic boom physical parameters and signature types, and (2) a possible insight into how people will respond to sonic booms in real life. Information is already available as to how people respond in real life to subsonic aircraft noise.

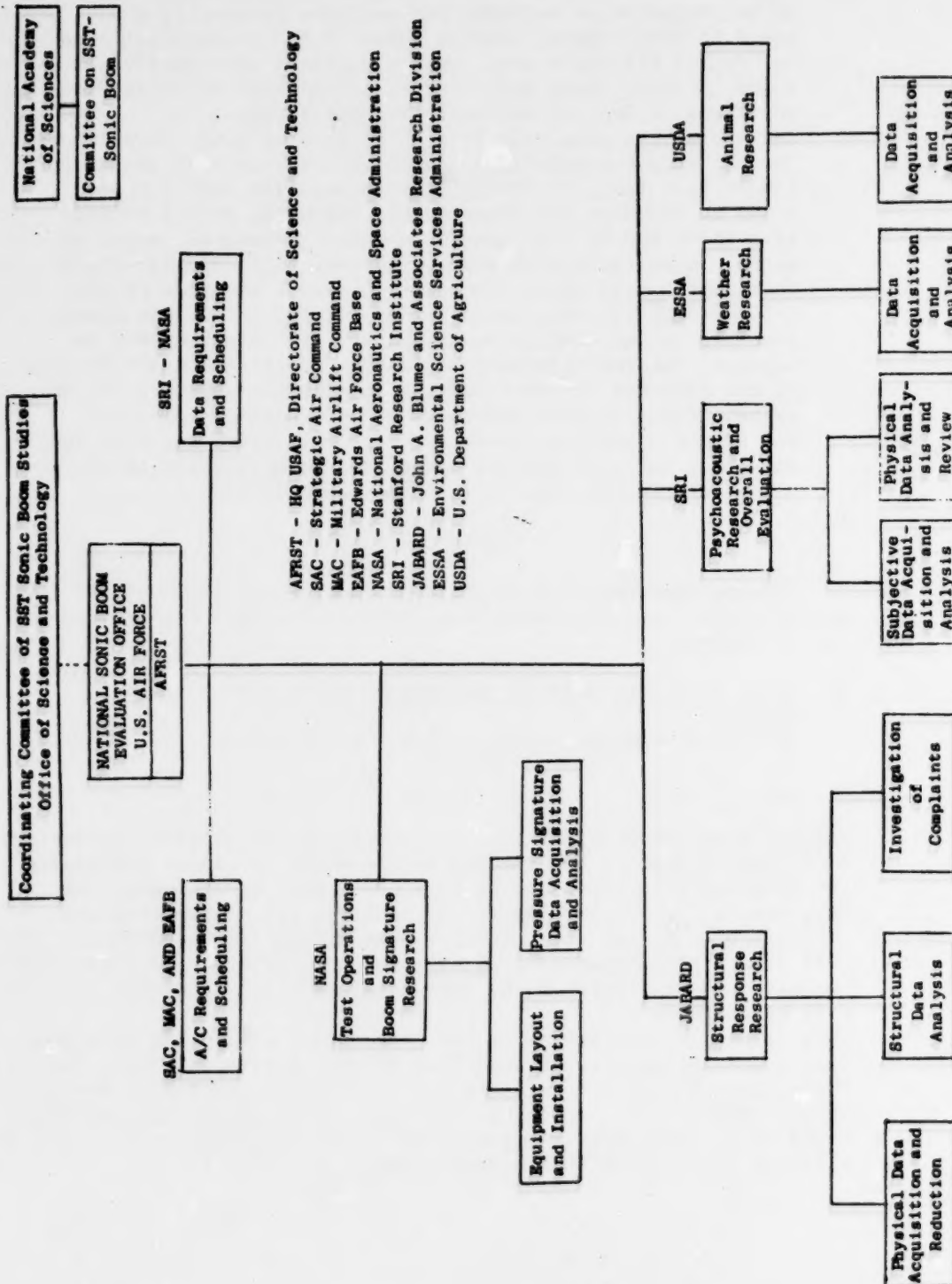


FIG. 4 ORGANIZATION CHART, EDWARDS AIR FORCE BASE EXPERIMENTS

4. The sonic booms and the noise from subsonic aircraft were to be presented to subjects who had been habitually exposed to sonic booms, such as those in the residential area at Edwards Air Force Base, and to subjects not usually exposed to sonic booms and aircraft noise, such as those from the towns of Fontana and Redlands, California.
5. The subjective judgments were to be made of sonic booms whose "normal"* peak overpressure level varied from 0.75 pounds per square foot (psf) to 3.0 psf, whose duration varied from 0.075 to 0.3 sec, and whose speed across the ground varied from about 900 to 1700 mph. To obtain the desired ranges of speed, duration, overpressure, and near-field and far-field boom signatures, three types of supersonic aircraft (F-104, B-58, and XB-70) were used. Unfortunately, it was not always possible to vary independently these various parameters because of inherent limitations in the operating characteristics of the aircraft. Flyover noise from subsonic aircraft was obtained from 4-engined turbojets without noise suppressors and from 4-engined turbofan aircraft when operating with landing power and with takeoff power; the intensity levels of the noise were varied from about 90 to 125 PNdB.**

SUMMARY OF FINDINGS

Major findings from analysis of the results obtained for the subjects and listening conditions involved in these experiments are as follows:

1. Sonic Boom from B-58 Judged Against Noise from Subsonic Aircraft
(a) When indoors, subjects from Edwards AF Base judged booms

* Nominal peak overpressure (or some other nominal physical parameter) of a boom is that to be expected on the basis of theory concerning the generation and propagation of sonic booms. Accordingly, the word nominal serves as a short and succinct way of labeling the aircraft operations, i.e., stating that a boom from a given aircraft will have a given nominal peak overpressure specifies, for practical purposes, the altitude, Mach, and weight at which the given aircraft will be operated.

** PNdB is a unit that indicates the intensities of a noise on a scale that approximates the response of the human auditory system. The PNdB values herein reported are the peak levels reached by the noise when flying over the subjects. The PNdB values are determined from sound level meter measurements of the noise after the noise has been filtered into 1/3 or full octave bands.

from the B-58 at 1.69 psf nominal peak overpressure outdoors to be as acceptable as the noise from a subsonic jet at an intensity of 109 PNdB* measured outdoors.

- (b) When indoors, subjects from the towns of Fontana and Redlands judged the boom from the B-58 at 1.69 psf nominal peak overpressure outdoors to be as acceptable as the noise from a subsonic jet at an intensity of 118 to 119 PNdB** measured outdoors.
- (c) The booms heard outdoors from the B-58 at 1.69 nominal peak overpressure were judged to be as acceptable as the noise heard outdoors from a subsonic jet at 105 PNdB, 111 PNdB, and 108 PNdB by subjects from Edwards AF Base, Fontana, and Redlands, respectively.
- (d) When indoors, 27 percent of the subjects from Edwards and 40 percent of the subjects from Fontana and Redlands combined rated the B-58 booms of nominal peak overpressure of 1.69 psf as being between less than "just acceptable" to "unacceptable."
- (e) When outdoors, 33 percent of the subjects from Edwards and 39 percent of the subjects from Fontana and Redlands combined, rated the B-58 booms of nominal peak overpressure of 1.69 psf as being between less than "just acceptable" to "unacceptable."
- (f) Residents of Edwards AF Base who served as subjects had been in residence there for an average of two years and had been exposed during that period to about four to eight booms per day of medium nominal peak overpressure of 1.2 psf and to subsonic aircraft noise occasionally having peak PNdB levels as high as 110 PNdB. The towns of Fontana and Redlands, on the other hand, were not under or near the flight track of supersonic aircraft and were occasionally exposed to subsonic aircraft at a peak level of about 95-100 PNdB.

2. Acceptability of Sonic Booms from Different Military Aircraft

- (a) When heard indoors and judged against the aircraft noise, the booms from the XB-70, B-58, and F-104 were for com-

* Noises having these PNdB values would be generated on the ground directly under the flight path of a turbofan aircraft at an altitude of 800 or 1400 ft., depending on whether landing or takeoff engine power settings were used.

** Noises having these PNdB values would be generated on the ground directly under the flight path of a turbofan aircraft at an altitude of 300 to 600 ft., depending on whether landing or takeoff engine power settings were used.

parable peak overpressures, equally acceptable. When heard outdoors and judged against aircraft noise, the boom from the B-58 was slightly less acceptable than the booms from the XB-70 and F-104 aircraft.

- (b) When one type of boom was judged against another type of boom at equal nominal peak overpressure, no consistent significant difference in their acceptability was measured in these tests.

3. Acceptability of Booms and Aircraft Noise as a Function of Their Intensity

The unacceptability of sonic booms, as a function of intensity, increases at about twice again as fast a rate as does the unacceptability of the noise from subsonic aircraft; i.e., in terms of judged unacceptability, an increase of 12 PNdB in intensity of a noise from a subsonic aircraft was equivalent to about a 6 dB increase (from 1 psf to 2 psf) in the intensity of a sonic boom.

4. Acceptability of Booms or Noises for Indoor Listening Compared to Outdoor Listening

The results averaged over all tests indicates that the booms and particularly the noise were rated slightly more unacceptable by the listeners outdoors than by the listeners indoors. Also, the precision of the judgments and rate of growth of unacceptability as a function of the intensity of the booms or noise was about 50 percent greater for listeners outdoors than indoors.

5. Relations Between Physical Measures of Sonic Booms and Judgments of Acceptability

Energy band spectral analyses of the booms showed that the energy in the band 20-200 Hz or 20-1000 Hz predicted the subjective judgments of the listeners located both outdoors and indoors as well as overall peak overpressure. The maximum contribution to the Perceived Noise Level in PNDBs calculated for the sonic booms from the F-104, B-58, and XB-70 is made in the frequency region from 20-500 Hz or so and is negligible below 20 Hz and above 500 Hz

6. Relations Between Physical Measures of Subsonic Aircraft Noise and Judgments of Acceptability

The following physical measures or calculated values from the physical measures are listed in the rank order, from best to worst, with which they predicted the judged acceptability of the takeoff and landing approach noise from the turbojet and turbofan subsonic jet aircraft used for these tests:

Indoor - EPNdB_t, EPNdB, Max Phons, dB(A), dB(N), Max PNdB, Peak PNdB_t, EEPNdB, Peak PNdB, Max PNdB_t, EEPNdB_t, dB(B), dB(C)

Outdoor - EPNdB_t, EEPNdB_t, EEPNdB, Max PNdB, EPNdB, Peak PNdB_t, dB(A), dB(C), dB(B)

7. Discrimination of Intensity Differences in Booms and Subsonic Aircraft Noise

- (a) On the average, two booms were judged relative to each other to be significantly different in acceptability when their nominal or measured peak overpressures differed by about 1 dB, and by about 2 dB when the two booms were compared indirectly by judging each against a reference aircraft noise.
- (b) On the average, two aircraft noises were judged relative to each other to be significantly different in acceptability when they differed by about 2 PNdB, and by about 3 PNdB when the two aircraft noises were compared indirectly by judging each against a reference boom.

8. Differences in Judgments of Subjects Located in Different Rooms and When on Vibration Isolation Pads

Systematic differences were found among some of the sub-groups of subjects located in different rooms in the test houses. When some of the subjects were exchanged among rooms, it was found that some of the differences were due to the test rooms and not to the subjects. The F-104 boom caused less displacement of at least some of the walls in the test houses than did the booms from the B-58 or XB-70 which caused about equal displacement. Placing the indoor and outdoor subjects on vibration isolation pads did not significantly change their judgments of the sonic booms relative to the noise from the subsonic aircraft.

9. Attitude Survey

An attitude survey of residents (15 percent of whom served as subjects in these experiments) at Edwards AF Base revealed that 26 percent rated the boom environment as being between less than "just acceptable" to "unacceptable" for the month of June, when there was an average of about ten booms per day at a median nominal peak overpressure of about 1.69 psf. Fourteen percent of the residents also rated the boom environment prior to June as being between less than "just acceptable" to "unacceptable." During this previous period, there were about four to eight booms per day at a median nominal boom level of 1.2 psf. Six percent rated the ambient daily aircraft noise and seven percent rated the street noise as being between less than "just acceptable" to "unacceptable."

10. Age and Sex of Subjects

Within the adult population studied, age and sex are not statistically significant factors in the ratings or paired-comparison of the unacceptability of sonic booms or the aircraft noises.

Discussion

Annex F analyzed detailed spectra of a number of boom signatures.

These data were used in the final report to determine what portion of the energy spectra was needed to predict human and community response and were instrumental in conclusion 5 above. Of greater interest perhaps is the text on page 55 of the final report, which states:

Table 14 [table 1 of this paper] shows the correlations found between acceptability ratings of sonic booms and various physical measures of the booms. It is of interest to note that the correlation between the rating and the measures that exclude information regarding the energy for frequencies below 20 Hz are as high or higher than the measures, including overall peak overpressure (P), which use energy below 20 Hz; compare in particular data in columns 4 and 5, En_{0-1000} vs. $En_{20-1000}$. Note should be made of the fact that the B-58 booms analyzed in this fashion covered such a restricted range of overpressures that only a few significant correlations were obtained.

It can be concluded from these data that it is not necessary, even perhaps slightly misleading, to measure sonic boom in ways that include the energy in sound frequencies below about 20 Hz and above, possibly less than, 1000 Hz if one is interested in predicting only the response of people and typical house structures to the booms. If one is concerned with the effects of the atmosphere on the propagation and of the aircraft design on the generation of booms it is, of course, appropriate to evaluate the total energy and waveform of a boom from 0 to 5000 Hz or so. Also, this conclusion may not apply to other types, for example "nearfield" signatures, of sonic boom pressure waveforms than those studied.

It may at first seem somewhat surprising that a major portion of the energy in the boom--that below 20 Hz--and the frequencies to which the ear is most sensitive--those above 1000 Hz--can be discarded for these boom measurement and evaluation purposes. As aforementioned, people and typical structures do not respond very much to the very low frequencies, and the energy in the frequencies above 1000 Hz is relatively very small in a sonic boom.

Annex G deals with the response of structures to sonic booms. Displacement measurements were made on outer walls and the roof of the test houses but, unfortunately, not on the inside floors. Maximum outer wall displacements were on the order of .02 inches. The resonant frequency for these walls was found to be on the order of 10 to 20 Hz. It can be

Table 1
RANK CORRELATIONS BETWEEN MEDIAN RATINGS AND VARIOUS ENERGY MEASUREMENTS
OF SONIC BOOMS RECORDED OUTDOORS

Subjects	Aircraft	Nominal ΔP (psf)	Number of Missions, N	Critical Value at 5% Level of Significance	Measure							
					AP	En ₀₋₅₀	En ₀₋₂₀₀	En ₀₋₁₀₀₀	En ₂₀₋₁₀₀₀	En ₂₀₋₂₀₀	En ₁₀₋₃₀	En _{Total}
Edwards Indoor ↓	XB-70	2.52, 2.06, and 1.36	5	0.81	0.90*	0.30	0.30	0.30	0.90*	1.00*	0.90*	0.30
	F-104	2.80, 1.40, and 0.75	18	0.40	0.93*	0.92*	0.92*	0.92*	0.94*	0.94*	0.92*	0.92*
	B-58	2.52, 2.33, and 2.06	12	0.50	0.32	0.31	0.31	0.44	0.53*	0.51*	0.27	0.44
Edwards Outdoor ↓	XB-70	2.52, 2.06, and 1.36	5	0.81	0.80	0.60	0.60	0.60	1.00*	0.90*	1.00*	0.60
	F-104	2.80, 1.40, and 0.75	18	0.40	0.89*	0.88*	0.87*	0.87*	0.90*	0.90*	0.88*	0.89*
	B-58	2.52, 2.33, and 2.06	12	0.50	0.32	0.42	0.42	0.39	0.17	0.17	0.14	0.39

* Rank Correlation greater than Critical Value.

Notes: 1. All judgments were made on the 1st sound of a pair of aircraft sounds.

2. The rank order correlation is defined as $1 - [6 \sum d^2 / N(N^2 - 1)]$ and d is the difference in ranks (in this case, the difference in the ranks of the median ratings and the ranks of the physical measurements). The critical value at the 5% level of significance varies with the value of N.

3. The subscripts of En (energy measures) indicate the limits of energy bands, e.g., En20-1000 designates an energy measurement in the band 20 Hz to 1000 Hz and is defined as the integral of the energy spectral density function between the limits 20 Hz to 1000 Hz.

expected that the floor vibrations and displacements will be lower than the outer wall and roof, therefore, according to data by Wiss and Parmalee,⁽²⁹⁾ the test house vibrations should be judged to be between slightly and distinctly perceptible--but not disturbing. Conclusion 8 of the final report substantiates this assessment. The subjects responded the same whether seated on the floor directly or seated on the vibration isolation pads.

Finally, it should be noted that there is a shift between outdoor and indoor responses as compared to sonic booms. Booms are found by the subjects to be relatively more annoying indoors than outdoors. This result is expected since the normal house attenuates booms far less than it attenuates aircraft noise, due to spectral differences in the signal. The comparisons indoors are felt to be the important ones since it is indoors that people spend most of their time, and since it is indoors that the secondary effects of building rattles and vibration play their primary role.

D. R. Johnson and D. W. Robinson (Applied Physics Division, National Physical Laboratory, Teddington, England), "The Subject of Evaluation of Sonic Bangs," Acustica, Volume 18, No. 5, 1967.⁽²²⁾

Summary

An experiment is described in which 61 subjects used the method of direct magnitude estimation to judge the relative annoyance of sonic bangs, explosions and jet aircraft noise. Artificial white noises were included to test the subjects' performance for individual consistency and to compare their results with the established relationship between subjective magnitude and objective level.

The annoyance of sonic bangs is shown to correlate closely with calculated loudness level, nearly as well with perceived noise level but poorly with peak overpressure. Conventional methods of calculation for steady sounds have to be modified to take account of the predominance of low frequency energy and of the short duration of sonic bangs. The appropriate band pressure levels are derived from the Fourier transform of the

waveform by averaging band energies over the auditory critical time of 70 ms. The same procedure is applied to the explosions. The relative annoyance of the transient sounds and of the jet aircraft and white noise are then correctly predicted.

The octave band sound pressure spectrum of the theoretical waveform for a ground-reflected N-wave is shown to agree with measured spectra of sonic bangs.

The subjective results are consistent with those of a laboratory experiment using recorded sonic bangs from a similar aircraft, the present results showing that a peak overpressure of 1.4 mb measured at ground level is as annoying as jet noise at 110 PNdB. For sonic bangs of different rise time this result would not apply.

The listening tests were repeated outdoors and indoors, and showed that subjects were about 5 phons more severe in their judgments indoors, in conformity with previous results on conventional aircraft noise.

Discussion

This test used white noise, door slams (indoors only), double explosions (to simulate a sonic boom), actual sonic booms, and common aircraft overflights. The subjects were tested both indoors and outdoors. It should be noted that the indoor tests were conducted in a brick-built barracks. As can be noted from the summary, the authors find that a pressure of 1.4 mbars (3 psf) correlates with 110 PNdB. It is noted that this is in relatively close agreement with their earlier work in the laboratory and with Kryter's findings at Edwards Air Force Base. Also, they find the same shift between indoor and outdoor judgments as was found by Kryter at Edwards. [Their slightly higher level (3 psf versus 2 psf earlier) is probably the result of using a brick test structure.]

Note must also be made of paragraph 2 of the summary above, where the authors indicate that peak overpressure correlates only poorly with subjective response, but that calculations using the spectrum of the signal correlate quite well with the subjective responses.

It should be noted at this point that Kryter, Robinson and the other investigators have created a somewhat misleading situation by usually

reporting their results in terms of peak sound level while continually stating in the fine print that energy spectra was the best way to analyze sonic booms and relate them to community and human response. Obviously, they used the peak levels in their reporting only as a convenience and for its historical value and not because they felt that this was the proper measure to correlate with human response.

D. R. Johnson and D. W. Robinson (National Physical Laboratory, Teddington, England), "Procedure for Calculating the Loudness of Sonic Bangs," Acustica, Volume 21, 1969. ⁽²³⁾

Summary

In a previous paper the subjective magnitude of sonic bangs was shown to be calculable from waveforms recorded during field experiments, using an adaptation of established loudness calculation procedures. The method used previously is now applied to model waveforms based on likely values of overpressure, duration and rise time with allowance for interaction between incident and ground reflected shock waves.

The determination of the energy spectrum by Fourier analysis of the waveform is described first; the way in which the standard loudness calculation for continuous sounds is adapted to the case of brief transients, such as sonic bangs with high levels of very low frequency energy, is then given in detail and summarized in an appendix.

The results of applying the procedure to waveforms broadly within the range anticipated from first generation supersonic transports, are quoted in graphical form; for a given nominal peak overpressure, loudness level is found to vary by as much as 25 phons for rise times and delays between 0 to 16 ms. Finally, it is shown that loudness levels may be considerably intensified by focussing such as may be produced by manoeuvring aircraft.

Discussion

Based upon their successful previous work correlating subjective loudness responses to sonic booms and performing calculations on the spectral analysis of the waveform, the authors established a detailed procedure to calculate loudness and analyzed a number of different waveforms using this procedure.

In the last part of the summary the authors discuss the loudness produced by manoeuvring aircraft. These so-called "super booms" have waveforms that in reality are almost identical to blast waveforms. Typically they have a sharp rise followed by a decay to a negative pressure, followed by a slower rise to ambient pressure. The negative phase is approximately two times as long as the positive phase in duration, and has an amplitude of somewhat less than 1/2 the peak amplitude of the positive phase.

The following paper describes the development of the impulse noise simulator at the Stanford Research Institute and the results of the first tests performed in the chamber.

Jerome S. Lukas and Karl D. Kryter (Stanford Research Institute), A Preliminary Study of the Awakening and Startle Effects of Simulated Sonic Booms, NASA Contractor Report 1193, 1968. (24)

Abstract

This report presents the results of experiments on the startling and awakening effects of sonic booms. The objectives of the study were (1) to build and test a device and associated room where one could simulate the effects of a sonic boom on a room in a house, and (2) to conduct studies of the effects of the simulated indoor booms on people sleeping and performing manual tasks. The findings are based on a study of a small, homogeneous group of subjects and, therefore, must be considered tentative at this time.

Discussion

This simulator was basically a floating room excited on one wall through a plenum space by a large piston. The piston was actuated by mechanical linkage and cams. The cams were machined to create the sonic boom or other required signal in the piston's motion. The room could be made to look like a small living room or bedroom. (See Figure 5).

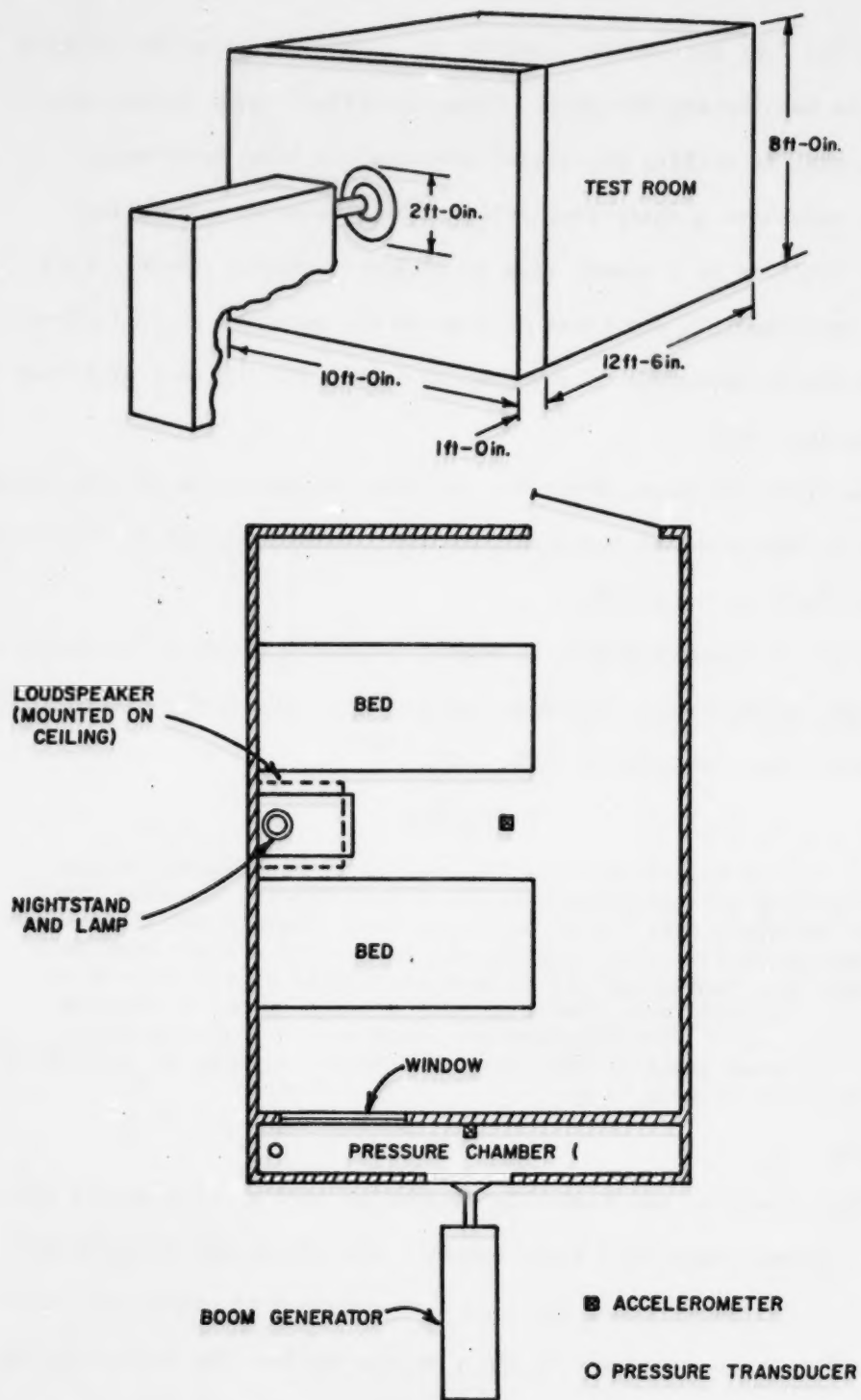


FIGURE 4 SCHEMATIC OF SONIC-BOOM STUDY FACILITY

Other studies included "The Awakening Effects of Simulated Sonic Booms and Subsonic Aircraft Noise on Six Subjects, 7 to 72 Years of Age", by Lukas and Kryter⁽²⁶⁾, the disturbance of human sleep by Lukas et al.⁽²⁷⁾ and the effects of aircraft noise on the sleep of women by Lukas and Dobbs.⁽²⁸⁾

The last major sonic boom annoyance study performed in the SRI simulator was done by Kryter and Lukas in 1971. K. D. Kryter and J.S. Lukas (Stanford Research Institute), Simulated Indoor Sonic Booms Judged Relative to Noise from Subsonic Aircraft, NASA CR2106, August 1972.⁽²⁵⁾

Abstract

Judgment tests were conducted in which subjects equated the subjective unwantedness or noisiness of simulated indoor sonic booms with the flyover noise of a subsonic jet aircraft as heard indoors. In agreement with previous studies, it was found that the spectral content of the booms, as affected by changes in the rise time of the booms, influenced the relative subjective noisiness of the booms in a way predictable from certain physical measures of Max PNL and EPNL. However, a correction factor is required for predicting from physical measures the subjective noisiness of sonic booms when compared to non-impulsive subsonic aircraft flyover noise measured in the same physical units. It appears that a somewhat different correction value is required for booms heard outdoors than when heard indoors.

Discussion

As can be seen by the abstract, no new findings are presented in this report. Rather it confirms much of the previous work. Rise-time, duration and spectrum are all factors in the subjective noisiness of booms. To fit within the Noise Exposure Forecast (NEF) scheme of prediction, Kryter proposed an impulse correction factor, since the EPNL for a boom judged equal to an aircraft flyover did not equal the EPNL for the aircraft flyover, at least with the stimuli presented.

2.5 Attitudinal Surveys - Boom Effects

During the period from 1962-1972, numerous attitudinal surveys were performed worldwide attempting to better understand community and human response to sonic booms. Webb and Warren⁽³⁰⁾ studied the response of a small village in England to booms simulated by explosive charges. Rylander et al.⁽³¹⁾ studied the responses of a small group of Swedish soldiers to supersonic aircraft overflights. The first major study was conducted by Nixon et al.⁽³²⁾ in the Greater St. Louis area in the early 1960's. This was followed by the classic Oklahoma City study by Borsky⁽³³⁾ in 1965 and the TRACOR⁽³⁴⁾ studies in Atlanta, Chicago, Dallas, Denver and Los Angeles. While Borsky performed his study in Oklahoma City, de Brisson⁽³⁵⁾ performed a major survey in France.

Since these studies indicate human and community response in actual sonic boom situations, the results implicitly include the effects of induced building vibration.

D. R. B. Webb and C. H. E. Warren (Royal Aircraft Establishment, Farnborough, Hampshire, England), "An Investigation of the Effects of Bangs on the Subjective Reaction of the Community", Journal of Sound and Vibration, Volume 6, 1967.⁽³⁰⁾

An investigation has been made, using explosive charges as the source of the bangs, of the effect of bangs on the subjective reaction of a community. Although the exercise had many imperfections, the two main facts that emerged were that the percentage of persons annoyed became less as the bangs became an established feature of the environment, and that the exchange rate found between the effect of frequency and the effect of intensity was not inconsistent with that implied by the Noise and Number Index concept introduced by the Wilson Committee on the Problem of Noise.

Discussion

In the first of the community survey types of studies discussed herein, Webb and Warren set off explosive charges suspended from a balloon 400 feet above the ground. The balloon was chosen in order to minimize the acoustical variability that had been found in earlier tests when charges were placed at ground level.

Webb and Warren's results are in agreement with the major American studies in form but not in absolute value. Frequency of event and amplitude of events correlate correctly with annoyance, but the absolute percentage of individuals annoyed is quite low compared to the American studies which follow. A probable explanation of this discrepancy offered by Kryter is that the inhabitants of the test Scottish village live in relatively old stone barracks on a military reservation and that these buildings attenuated the noise more, and vibrated less, than a conventional frame house does.

By way of comparison, Rylander et al. also performed a small survey on their test staff and a small number of military recruits as part of a study which primarily dealt with the effect of sonic booms on structures.

R. Rylander et al. (Department of Environmental Hygiene, National Institute of Public Health, The Institute of Hygiene, Karolinska Institute and the Institute of Sociology, Stockholm University, Stockholm, Sweden), "Experiments on the Effect of Sonic Boom Exposure on Humans", Journal of the Acoustical Society of America, Volume 51, 1972.⁽³¹⁾

This paper reports the results of a field experiment initiated by the Division of House Construction at Chalmers' University of Technology in Connection with the Swedish Aeronautical Research Institute, whose primary aim was to study boom exposure effect on structures. Military aircraft

were used which flew over a test area generating sonic booms of various intensities. Test persons were exposed directly under the flight path, the exposure effect being measured with the aid of a visual performance test and a tracking test. In addition, the subjective reactions of the test persons and military recruits, present at other sites under the sonic boom carpet, were evaluated with the aid of a questionnaire.

Discussion

The results of this study with the Swedish military recruits showed that a much higher percentage of the group was "highly annoyed" than was found in the American studies and that a far higher percentage was "highly annoyed" than was found by Webb and Warren. The authors speculate that the higher degree of annoyance resulted from negative attitudes about the booms on the part of the recruits and inexact knowledge as to the boom amplitudes.

The first major American study was reported by Nixon and Hubbard in 1965.

C. W. Nixon (Air Force Aerospace Medical Research Laboratory) and H. H. Hubbard (NASA Langley Research Center), Results of USAF-NASA-FAA Flight Program to Study Community Response to Sonic Booms in the Greater St. Louis Area, NASA TND-2705, May 1965.⁽³²⁾

Summary

Data are presented from a series of community-reaction flight experiments in which the population of a large city was repeatedly exposed to sonic booms in the range of overpressures up to about 3.1 lb/sq ft. Results were obtained from direct interviews, analyses of complaint files, and engineering evaluations of alleged damage and are correlated with information on aircraft operations and sonic boom pressure measurements.

Personal-interview studies indicated that about 90 percent of those contacted experienced some interferences as a result of sonic booms, about 35 percent were annoyed by them, less than 10 percent had contemplated some complaint action, and less than 1 percent had actually filed a formal complaint. The total number of complaints and subsequent claims were approximately proportional to the number

of flights. Building responses are a significant factor in community response. Alleged building damage was superficial in nature and consisted mostly of cracks in brittle surfaces. Contributing factors other than sonic booms were noted in most of the damage cases. There were no reports of direct adverse physiological effects.

Discussion

This study, being the first, did not employ all of the measurement techniques found useful in subsequent studies. Thus, only qualitative, and not quantitative, use can be made of the results. Nevertheless it is useful to note that less than half the respondents finding that booms cause interference also indicated annoyance. Further, only ten percent of the respondents contemplated complaints and less than one percent actually filed a formal complaint.

The authors conclude that an annoyance reaction requires interference as a prerequisite and that the 35 percent of respondents expressing annoyance are a subset of the 90 percent expressing interference. Similarly, the ten percent contemplating complaint are a subset of the 35 percent annoyed. The authors based this conclusion upon the fact that their data met the requirements of a Guttman scale of intensity of interference.

Along with the Edwards Air Force Base study,^(20,21) the Oklahoma City test⁽³³⁾ represents the other major quantitative U.S. study dealing with human and community response to sonic booms.

Paul N. Borsky (National Opinion Research Center), Community Reactions to Sonic Booms in the Oklahoma City Area, Aerospace Medical Research Laboratories, AMRL-TR-65-37, October 1965.⁽³³⁾

Summary

During a period of six months from February to July, 1964, the Oklahoma City, Oklahoma, area was repeatedly exposed to sonic booms generated to simulate overpressure levels that are expected for supersonic transport overflights. The schedule provided for eight sonic booms per day. During the six-month period, almost 3,000 local residents were interviewed three times to determine the nature and extent of their reactions to the sonic booms. This report contains a detailed description of the overall study design including the selection of households, selection of respondents, training and selection of interviewers and samples of questionnaires used during the interviews. Among the findings it was determined that ordinary living activities were often interrupted by sonic booms, but that a majority of the residents felt they could learn to live with the interruptions. A substantial number of residents felt they had sustained damages from the booms, although detailed engineering observations of structures in the area did not confirm most of these reports. As the intensity of the booms increased, acceptance of the booms by residents was reduced. Residents who felt that the development of a commercial supersonic airplane was important were more likely to accept the exposures to the sonic booms.

Discussion

In the Oklahoma City test, Borsky reports on interference with ordinary living activities, annoyance with sonic boom, desires to complain and actual complaints about sonic booms, and long-range acceptability of sonic booms. The test covered three time periods. During the first period (February 3 to April 19, 1964) the medium boom level under the flight path was 1.13 pounds per square foot; during the second period (April 20 to June 14), 1.23 psf; and during the third period (June 15 to July 25), 1.6 psf. There were correspondingly lower levels at distances of eight to twelve, and twelve to sixteen miles from the flight path. (Table 2.)

Borsky's Table 1, Table 81, Table 84, and Table 102 present some of the most utilized and often-quoted data for predicting impulse noise effects. For convenience, these are reproduced. Table 1 (this report's Table 2) presents the actual nominal overpressures by distance from flight

Table 1

MEDIAN SONIC BOOM OVERPRESSURES BY DISTANCE FROM GROUND TRACK				
Oklahoma City Area February-July 1964				
<u>Time Period</u>	<u>No. Weeks</u>	<u>Miles from Ground Track</u>		
		<u>0-8 Overpressure (psf)</u>	<u>8-12 Overpressure (psf)</u>	<u>12-16 Overpressure (psf)</u>
February 3- April 19	11	1.13	0.80	0.65
April 20- June 14	8	1.23	1.10	0.85
June 15- July 25	6	1.60	1.35	1.00

Table 3 (After Table 81, Borsky)

REPORTED TYPES AND FREQUENCY OF INTERFERENCE BY SONIC BOOMS
BY DISTANCE FROM GROUND TRACK

Oklahoma City Area

February-April 1964

Type and Frequency of Interference	Total	Miles from Ground Track		
		0-8	8-12	12-16
Number of Respondents	2019	1037	351*	336
House rattles-Total	89.0%	89.1%	90.6%	86.0%
Very often	29.5	36.4	22.8	15.5
Fairly often	27.1	27.8	29.1	22.3
Occasionally	32.4	24.9	38.7	48.2
Startles-Total	39.2%	39.6%	38.2%	28.9%
Very often	8.1	11.0	5.1	2.7
Fairly often	8.9	9.6	9.4	5.1
Occasionally	22.2	19.0	23.7	21.1
Interrupts Sleep-Total	14.3%	15.2%	13.4%	6.0%
Very often	3.3	4.2	2.6	1.8
Fairly often	3.1	4.3	2.8	-
Occasionally	7.9	6.7	8.0	4.2
Interrupts Rest-Total	10.8%	11.0%	11.5%	6.0%
Very often	3.2	4.0	2.8	1.5
Fairly often	2.7	3.1	3.0	1.2
Occasionally	4.9	3.9	5.7	3.3
Interrupts Conversation-Total	9.0%	9.2%	9.3%	4.8%
Very often	1.8	2.2	1.9	.6
Fairly often	1.5	1.5	1.9	.9
Occasionally	5.7	5.5	5.5	3.3
Interrupts Radio & TV-Total	7.2%	7.1%	6.6%	3.6%
Very often	1.6	1.8	1.4	.3
Fairly often	1.4	1.4	2.0	.6
Occasionally	4.2	3.9	3.2	2.7

* Includes only persons living and working in some distance areas.

Table 4 (After Table 84, Borsky)

REPORTED ANNOYANCE WITH SONIC BOOMS
BY TYPE OF INTERFERENCE AND DISTANCE FROM GROUND TRACK

Oklahoma City Area
February-July 1964

Type of Interference and Intensity of Annoyance	Total	Distance from Ground Track											
		0-8				8-12				12-16			
		2/3	4/20	6/15	7/25	2/3	4/20	6/15	7/25	2/3	4/20	6/15	7/25
Number of Respondents	2019	2026	1915	1037	1045	989	351	351	331	336	335	314	314
House rattles-Total	54.3%	66.0%	73.1%	54.3%	68.2%	74.8%	56.6%	55.3%	67.7%	46.2%	56.7%	60.6%	60.6%
Very annoyed	15.4	24.4	32.8	16.6	25.9	35.3	12.5	19.4	25.4	5.1	11.0	16.9	16.9
Moderately annoyed	17.7	19.6	20.7	17.8	20.3	20.6	17.9	16.8	20.8	14.6	19.7	18.5	18.5
Little annoyed	21.2	22.0	19.6	19.9	22.0	18.9	26.2	19.1	21.5	26.5	26.0	25.2	25.2
Startles-Total	30.0%	31.1%	35.4%	30.6%	32.2%	37.0%	28.4%	26.7%	29.1%	20.3%	21.3%	22.3%	22.3%
Very annoyed	9.2	12.0	16.1	9.8	12.5	16.8	7.1	9.1	12.7	3.3	4.5	7.6	7.6
Moderately annoyed	10.3	9.8	11.6	10.5	10.1	12.6	10.5	9.1	7.3	5.4	8.4	8.6	8.6
Little annoyed	10.5	9.3	7.7	10.3	9.6	7.6	10.8	8.5	9.1	11.6	8.4	6.1	6.1
Interrupts Sleep-Total	12.0%	13.1%	16.2%	12.7%	14.9%	17.5%	10.8%	6.0%	10.2%	4.8%	7.5%	8.3%	8.3%
Very annoyed	4.9	6.7	9.2	5.2	7.3	9.9	4.6	4.0	5.7	1.2	2.1	4.5	4.5
Moderately annoyed	3.7	3.9	4.9	4.1	4.6	5.6	3.1	1.4	1.8	1.5	3.3	2.2	2.2
Little annoyed	3.4	2.5	2.1	3.4	3.0	2.0	3.1	.6	2.7	2.1	2.1	1.6	1.6
Interrupts Rest-Total	9.7%	12.2%	16.6%	10.1%	12.8%	17.7%	9.4%	10.0%	13.6%	4.8%	6.6%	8.6%	8.6%
Very annoyed	5.2	6.8	10.6	5.3	6.9	11.5	4.3	6.0	8.2	1.8	3.3	5.1	5.1
Moderately annoyed	2.8	3.8	3.8	3.1	4.0	3.8	2.8	3.7	2.7	2.4	2.1	2.5	2.5
Little annoyed	1.7	1.6	2.2	1.7	1.9	2.4	2.3	.3	2.7	.6	1.2	1.0	1.0

Table 5 (After Table 102, Borsky)

REPORTED THRESHOLDS OF ACCEPTABILITY OF SONIC BOOMS
BY DISTANCE FROM GROUND TRACK

Oklahoma City Area

February-April 1964

<u>Number of Booms Acceptable</u>	<u>Total</u>	<u>Distance from Ground Track</u>		
		<u>0-8</u>	<u>8-12</u>	<u>12-16</u>
Number of respondents	2033	1048	352	337
<u>10-12 Booms per Day</u>				
Very likely	64.1%	63.4%	63.4%	70.9%
Might	19.7	19.6	17.9	19.6
Could	83.8%	83.0%	81.3%	90.5%
Couldn't	14.1	14.8	17.0	7.7
Don't know	2.1	2.2	1.7	1.8
<u>8 Booms per Day</u>				
Very likely	75.3%	74.8%	73.3%	80.4%
Might	15.9	15.8	15.1	14.8
Could	91.2%	90.6%	88.4%	95.2%
Couldn't	6.2	6.5	8.8	3.6
Don't know	2.6	2.9	2.8	1.2
<u>5-6 Booms per Day</u>				
Could accept 8	91.2%	90.6%	88.4%	95.2%
Very likely	.3	.4	.3	.3
Might	1.2	1.5	1.4	.6
Could accept 5-6	92.7%	92.5%	90.1%	96.1%
Could not	5.1	5.1	6.8	3.6
Don't know	2.2	2.4	3.1	.3
<u>1-2 Booms per Day</u>				
Could accept 5-6	92.7%	92.5%	90.1%	96.1%
Very likely	.7	.8	.9	-
Might	2.3	2.3	2.6	1.8
Could accept 1-2	95.7%	95.6%	93.6%	97.9%
Could not	3.0	3.4	4.3	1.8
Don't know	1.3	1.0	2.1	.3

track and time period; Table 81 (Table 3) lists type of interference by distance from flight track and time period; Table 84 (Table 4) lists degree of annoyance by distance from flight track and time period; and Table 102 (Table 5) lists ability to accept 8 booms per day by distance from flight track.

As with the Nixon study, complaints represented only a very small subset. During the last time period, for which the booms were greatest in amplitude, only 0.7 percent of respondents were complainants. Borsky indicates that complaints result only when the respondent is annoyed, feels it is not unpatriotic to complain, has the knowledge of how to complain effectively, feels that his complaint will do some good, and believes that the noise is harming his family or house.

The last major American survey is the TRACOR study⁽³⁴⁾ at five major American cities.

TRACOR, Inc., Public Reactions to Sonic Booms, NASA CR1665, September 1970.⁽³⁴⁾

Abstract

This report assesses the nature of public reaction to sonic booms in selected metropolitan areas of the United States, and identifies the major social or psychological factors that are associated with one or another type of public reaction to sonic booms of relatively modest overpressure levels. The sonic booms were generated by the supersonic DR-71 reconnaissance airplane during air force training and test flights. A bibliography of boom studies and a bibliography re news media studies are included. A tentative causal model relating the hearing of sonic booms to attitudes and reactions indicates that a negative attitude to the boom must be developed before the respondent reports an increase in disturbance of his activities. It is this disturbance of activities that then relates to the level of annoyance of the respondent. The importance of this finding is that the reaction pattern appears to be different for sonic booms and subsonic aircraft noise. Although the evidence is limited and it is hoped that further work of this nature can be done.

Discussion

Unfortunately, the authors did not record distance from flight track as Borsky had done in the Oklahoma City study. Therefore, as with the St. Louis study⁽³²⁾ only qualitative judgments can be made about the data, because the exact level of exposure is not known.

In the latter part of the above abstract, the authors indicate the need for a "negative attitude" towards the boom before respondents will report an increase in disturbance of activities. The authors imply that this factor is not important when considering annoyance of subsonic aircraft. The authors developed their measure of attitude by observing the adjectives that respondents used to describe the boom. For example, the adjectives "startling" was considered negative, whereas the adjective "thrilling" was considered positive.

It does seem plausible that a respondent finding the sonic boom thrilling would not find it annoying. However it seems equally plausible that the same is true for subsonic aircraft. That is, an individual who finds subsonic aircraft noises to be thrilling would not find them annoying. It seems clear that the same would also be true for open-pit mining noise. (Recall, Rylander et al.⁽³¹⁾ suggests that the large percentage of annoyance resulted from a negative attitude toward sonic booms.)

The TRACOR studies sought to separately distinguish complainants from non-complainants. Perhaps their most useful finding is that there were no real differences in the socio-economic level of complainants. The only real difference they found between complainants and non-complainants was that 90 percent of the complainants owned their homes and felt that the boom damaged their homes. It follows that the same type of relationship might exist with respect to open-pit mining noise.

In general, the disturbance and annoyance levels reported in the TRACOR study are very close to (and usually a little larger than) the Oklahoma City findings. However, as pointed out above, only qualitative use can really be made of this data, because definitive knowledge of boom amplitudes is lacking.

M. de Brisson, "Opinion Study on the Sonic Bang," Royal Aircraft Establishment Library translation number 1159, April 1966, AD483066. (35)

In 1965, approximately 2300 personal interviews were conducted in the eastern (Strasbourg area) and southwestern (Bordeaux area) of France, to assess the community response to the military aircraft routinely creating sonic booms over these regions, and to project the acceptability of future SSTs to the population. No booms were specifically generated for this test. Hence, as with the St. Louis study and the TRACOR study, no data on the physical stimulus is available. In addition, for this study, the number of booms is unknown.

It was found that:

- (1) interference with daily living activities was similar to that in St. Louis and Oklahoma City;
- (2) 34 percent of the respondents felt they could definitely not live with ten booms per day (this is a higher percentage than in the Oklahoma City study);
- (3) the belief that the boom damaged property or caused personal injury was a significant factor in the development of an annoyance response;
- (4) the respondents did not want to see an Oklahoma City-type study performed in France.

2.6 Studies Relating to Noise From Explosives

P. Schomer (Construction Engineering Research Laboratory),
Predicting Community Response to Blast Noise, CERL Report E-17, 1973.⁽³⁶⁾

Abstract

This report presents a preliminary method for predicting levels of annoyance from artillery or blast noise in the environs of a military base. The means are given to relate various artillery pieces to a TNT equivalent and to normalize the overpressure from the detonation of one pound of TNT. Buried charges and aboveground detonations are also considered. Various ways to predict probable blast overpressure and frequency spectrum as a function of distance are discussed.

The annoyance of man by blast noise is predicted using the composite noise rating (CNR) and, for this calculation, the impulsive noise startle correction factor suggested by Kryter is added to the perceived noise level. Because CNR is utilized, the prediction method is suitable for computer computation of equal annoyance contours. Blast noise case histories are considered and serve to verify the prediction method. Additional data and tests are needed to more accurately predict blast pressure spectrum levels and the precise reaction of man to these blasts.

Discussion

Schomer⁽³⁶⁾ proposed the use of EPNL with the impulse correction proposed by Kryter to assess human and community response to the blast noise created by armor, artillery, and demolition. The impulse-corrected EPNL proposed by Kryter^(25,37) was chosen so that the resulting community response predictions would be compatible (CNR/NEF units) with other predictions made within the Department of Defense dealing with aircraft noise.

This 1973 report does not present the results of new tests. Rather it seeks to extend knowledge in related areas to the problem of blast noise resulting from armor, artillery, and demolition. As such, it draws upon much of the literature presented above.

Continuing chronologically, in 1974, Taylor, Kende, and Scott⁽³⁸⁾

analyzed human annoyance to quarry blasts. The National Academy of Science⁽³⁹⁾ and the U.S. EPA proposed a C-weighted day/night measure to assess large amplitude impulse noise, including open-pit mining operations, artillery and armor fire, demolition, sonic booms and other industrial impulsive sources. In that same year Young⁽⁴⁰⁾ reported on a blast noise study using the sonic boom simulator facility at the Stanford Research Institute. For this study, the simulator was modified to create blast-type sounds similar to those resulting from artillery fire. Finally, in 1977, Schomer⁽⁴¹⁾ completed an additional analysis of the Young data which supported the EPA's C-weighted procedure.

A. G. Taylor and L. G. Kende (Noise Pollution Control Section, Ontario Ministry of the Environment), and D. F. Scott (Department of Mechanical Engineering, University of Toronto), Quarry Blast Atmospheric Wave Concussion: Response of Structures and Human Annoyance; Ministry of the Environment, Ontario, Canada, 1974.⁽³⁸⁾

Abstract

A series of quarry blasts was monitored to determine if the acoustic wave was likely to be of significance from the points of view of structural damage and human annoyance.

The characteristics of the blast wave, overpressure, spectrum and duration were studied and compared with the characteristics of sonic booms.

The relative significance of ground vibration and air-blast were studied and simultaneous vibration and overpressure measurements taken.

The two phenomena were shown to be similar in spectral content. The overpressure at several thousand feet from a blast can be similar to that of a sonic boom and the duration of the pressure perturbation is several times longer for a blast than for a sonic boom.

Discussion

Since this study dealt with quarry blast noise, it is of particular interest here. In part, it concluded:

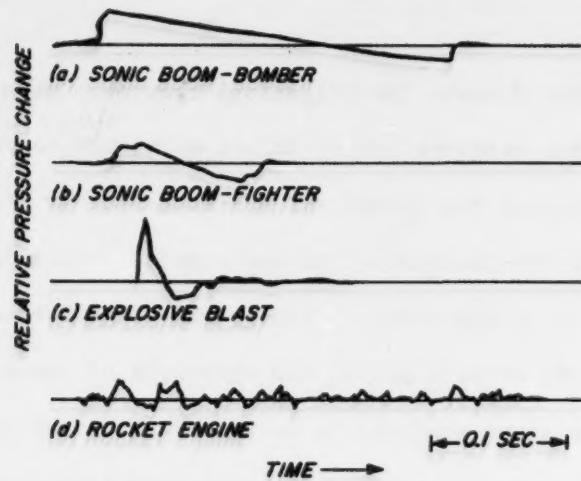
"The experiments carried out have shown that the acoustic wave associated with a quarry blast bears some close resemblances to the pressure signature of a sonic boom.

The overpressures experienced up to several thousand feet from a blast can be of the same order as those produced by sonic boom.

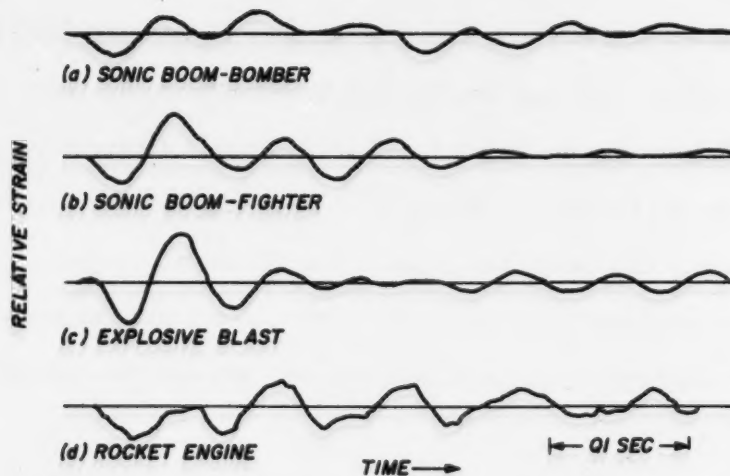
The spectra are very similar with a maximum amplitude in the low infrasonic range and little contribution above 500 Hz. The blast tends to have a relatively greater contribution in the low sonic range which would make it subjectively louder than the boom for the same peak overpressure."

Figures 2 and 3 of the Taylor report (Figures 5a and 5b) relate to the loading and resulting transient strain response for a vertical stud of a test building to the various input pressure loads. The strain responses are very similar from one load to another. The four loads, however, are quite different: a sonic boom from a bomber, a sonic boom from a fighter, an explosive blast, and a rocket engine. From these figures follow the expected conclusion that the building or structure vibration is at its natural frequency and proportional to the impulse energy in that frequency range.

Most interesting, perhaps, is the author's discussion dealing with seismic effects. They report on investigations into annoyance due to "vibration" in subways in Toronto, which cause an increase in sound level in adjacent homes of about 12 dB(C). At the same time, the vibration velocity level in the homes is about 0.2 inches per second which the authors indicate as the approximate threshold of human perception.



a TYPES OF PRESSURE LOADING FOR WHICH RESPONSE MEASUREMENTS WERE OBTAINED.



b TRACING OF TRANSIENT STRAIN RESPONSES FOR A VERTICAL STUD OF THE TEST BUILDING CORRESPONDING TO THE PRESSURE LOAD OF a. ABOVE

FIGURE 5 (AFTER TAYLOR et al, REFERENCE)

The authors also discuss investigations they have made of several noise-vibration problems due to impact machinery, where the energy was transmitted via the ground and manifested as low frequency airborne sound inside the residence. In such cases the complaint was invariably referred to as vibration, although the vibration level proved to be in the region of, or well below, the threshold of perception. However, the airborne sound produced by such small movement in the floor and walls of the structure did cause very high sound levels and did excite secondary noise sources such as windows and bric-a-brac. (Note: A new report by Wiss and Parmelee⁽²⁹⁾ substantiates these levels of vibration as being just barely perceptible.)

In 1975 and early 1976, the National Academy of Science Committee on Hearing Bioacoustics, and the Biodynamics Working Group 69 developed a C-weighted day/night average sound level measurement technique for assessing large amplitude impulse noise.⁽³⁹⁾ This was done as a part of efforts to develop the means for federal facilities to assess the impact of their operations. EPA recommended this C-weighted measure to other federal agencies on an interim basis and DOD has adopted this procedure.

The C-weighted average sound level was chosen as a suitable descriptor because it provided the basis of a procedure that could relate to the sound induced vibrations in buildings. C-weighting is a standard weighting curve which includes sufficient amounts of low frequency energy responsible for inducing building vibration, and at the same time excludes low frequency energy which lies below the building response range and is inaudible. Criteria levels were established by equating the percent

of population highly annoyed by sonic booms at various C-weighted levels to the percent of population highly annoyed by more normal noises (primarily aircraft and traffic noise survey data) at various A-weighted day/night average levels. The Edwards Air Force Base⁽²¹⁾ and Oklahoma City⁽³³⁾ studies were the primary basis for this procedure for assessing large amplitude impulsive sounds.

Analysis of the data showed that approximately the same percentage of the population was highly annoyed in an environment having an impulsive C-weighted day/night level of 60 dB as was a population in an area with an A-weighted day/night level of 60 dB. Because of the equivalency of the two measures on a percent highly annoyed basis, assessment of the overall noise environment can be made by combining the effects of impulsive sounds described using C-weighted and other sounds described using A-weighting.

The final report of Working Group 69 was published in 1977. Because Working Group 69 had a very large scope of work, Working Group 84 was formulated to reinvestigate just the issue of community response to impulsive noise. They reaffirmed the use of the C-weighted day/night level to assess impulsive noise. The report from this working group is due in 1978.

In 1976, Young⁽⁴⁰⁾ reported on the study of psychological annoyance of simulated explosion sequences.

J. R. Young (Stanford Research Institute), Measurement of the Psychological Annoyance of Simulated Explosion Sequences (2nd year), February 1976.⁽⁴⁰⁾

Abstract

Thirty subjects--18 females and 12 males--were exposed to a sequence of noises that included simulated artillery firing, aircraft flyovers, and some other noises that are frequently heard inside homes. Psychological response to the noises was measured in terms of annoyance by the method of magnitude estimation. An aircraft noise was used to establish a standard value of annoyance.

The psychological data were correlated with various physical measures of the noise stimuli. It was found that sound exposure levels--calculated with A-, C-, or D2-weighted sound pressures--were excellent predictors of response to these noises as heard indoors, particularly if the stimuli were separated into classes containing only simulated artillery noise or aircraft noise. Sound exposure levels (D2-weighted) were slightly better predictors than the other measures over the entire set of stimuli, but the sound exposure level (C-weighted) is recommended as a practical and generally useful measure for predicting indoor subjective response for noise stimuli similar to those used in this experiment.

Discussion

In this study, a special testing room at SRI, originally designed for testing human response to sonic boom, ⁽²⁴⁾ was modified to create artillery-type sounds. In a quasi-random sequence, subjects judged the annoyance of various artillery-type sounds (different amplitudes, durations, etc.) in relation to recorded aircraft flyover sounds, breaking glass sounds, and air horn sounds. The subjects used magnitude estimation procedures to assign annoyance values to the various noise stimuli presented.

It should be noted that all of the data presented in the report were for indoor sounds. That is, the blast energies were measured indoors, the aircraft flyovers were presented and measured after being filtered through a "house filter," a glass breaking is an indoor sound, and the air horn was filtered by the double walls of the test chamber. As is

shown in the following paper, when these sounds are corrected to their outdoor equivalent, the results show that the C-weighted blast measure is indeed equivalent in community response to the A-weighted day/night measure for other sounds. This equivalence occurs when the C-weighted sound exposure levels (SEL) are in excess of 85 dB--that is, when one considers moderate to large blasts in contrast to small blasts such as rifle fire or distant artillery.

Figure 6 of the Young report shows the growth function for artillery noise as compared to the growth function for aircraft noise. As in earlier works by Kryter and Lucas⁽²⁵⁾ and by Kryter⁽³⁷⁾ the growth functions are unequal. However, applying the 85 dB cut-off criteria eliminates the low level data making it clear that the C-weighted growth function at higher amplitudes is identical to the growth function for aircraft and other noises.

In 1977, Schomer⁽⁴¹⁾ translated or corrected the Young data from indoors to outdoors. Paul D. Schomer (Construction Engineering Research Laboratory, Champaign, Illinois), "Evaluation of C-weighted L_{dn} for Assessment of Impulse Noise", Journal of the Acoustical Society of America, Volume 62, 1977.⁽⁴¹⁾

Abstract

Community response to impulsive noise, such as sonic boom, artillery fire, and other military ordnance, and quarry and mining operations, is currently a matter of great public interest. Recently, the EPA has proposed the use of the C-weighted day/night level to estimate community response to large amplitude single-event impulsive noise. This measurement and its associated exposure criteria have been derived largely on the basis of existing community response to sonic boom data. Recent laboratory measurements of human reaction to artillery-type noise, reported on herein, strongly support this C-weighted measure.

Discussion

This paper clearly shows that C-weighted SELs of blast noise fall right in line with A-weighted SELs for other noises, ignoring impulses having C-weighted SELs below 85 dB. As with the earlier studies by Kryter at Edwards Air Force Base⁽²¹⁾ and Robinson⁽²²⁾ in England, it should be noted that building attenuation is typically less for blast noise than it is for aircraft and other environmental noises. This factor partially explains the observed indoor versus outdoor human response shift.

2.7 Summary Reports, Physiological Damage and a Reading Guide

Summary Reports:

In addition to the papers describing tests and studies discussed above, a number of summary papers have been written concerning sonic boom and impulse noise. These include papers by von Gierke^(42,43) published in 1966 and 1972, a paper by Kryter⁽⁴⁴⁾ in 1969, and a paper by Borsky⁽⁴⁵⁾ in 1966. These four are good papers and are recommended to the reader. Kryter's book, Effects of Noise on Man,⁽³⁷⁾ is also a good reference.

In 1976, Sutherland, Lee and Burke⁽⁴⁶⁾ reported on annoyance, loudness and measurement of impulsive noise sources. This report for the U.S. EPA deals largely with low level continuous impulsive sources such as jackhammers, motorcycles, etc. Although not directly related to sonic booms or quarry blasts, the report may be of use and interest to the reader.

Physiological Damage:

A study by Nixon, Hille and Sommer⁽⁴⁷⁾ indicates that sonic

boom, and presumably, open pit mining blasts, will not cause physiological damage in the community. The abstract of their paper is included below.

Abstract

Sonic booms generated by F-4C aircraft flying low-level terrain-following profiles during Joint Task Force II operations near Tonopah, Nevada, were recorded under and near the flight tracks, and responses of structures, animals, and people were observed. Recorded overpressures up to 144 psf were analyzed, correlated with available aircraft operations data, and compared with data from different aircraft flying similar profiles. Observations of structures, animals, and people were correlated with the measured overpressures. Results include acquisition of near-field recordings of overpressures generated by F-4C, the finding that some window glass fragments were propelled a short distance rather than falling directly below the window, an instance in which the measured overpressure of a sonic boom 1 mile to the side of the track far exceeded the predicted value, the finding that livestock (undetermined prior exposure to acoustic stimuli in this situation) did not respond adversely to the sonic booms, confirmation that very intense sonic booms do not harm people directly and the reaffirmation that the selection of site locations for low-level supersonic training missions will continue to pose a problem.

Reading Guide:

A substantial number of documents have been listed and discussed above. The casual reader may not wish to study all of these documents. In addition to the four summaries listed above, the Edwards Air Force Base study,^(20,21) the Shepherd and Sutherland report,⁽¹⁹⁾ the Fidell and Pearsons report,^(14,15) and the various Robinson studies^(16,22,23) are recommended for initial reading. The Borsky report⁽³³⁾ contains a wealth of data but is difficult to interpret. Because of the nature of the blasting problem, the Canadian study is also recommended, as are the Young⁽⁴⁰⁾ study and the recent Schomer article (for convenience, included in Appendix C).

CHAPTER 3

RESPONSE TO IMPULSE NOISE

3.0 Introduction

In Chapter 2 virtually all of the pertinent literature dealing with human and community response to impulse noise was presented and reviewed. In this chapter a "bridge" will be developed between this large body of data and the question of human response to open-pit mining noise. This bridge will be developed by posing a series of questions and drawing the answers from the literature presented.

3.1 What type of noise measure is best for predicting human response to impulse noise?

Kryter⁽²⁰⁾ in the Edwards Air Force Base study found that the frequency-weighted energy in approximately the 20 to 500 Hz band offered the best measure for correlation with annoyance.

Zepler and Harel⁽¹⁷⁾ and Shepherd and Sutherland⁽¹⁹⁾ both found spectrum important to establish the loudness of sonic booms and other impulsive sounds, and also that the energy below about 40 Hz contributed virtually nothing to the perception of loudness.

Johnson and Robinson⁽²²⁾ found that "the correlation between annoyance and peak overpressure was poor and that a better result was obtained if the sonic bangs [booms] are evaluated in terms of loudness level." In effect, then, Johnson and Robinson use a frequency-weighted measure

which cuts out the very low frequencies (below about 20 Hz) and integrates the signal over all time to obtain a frequency weighted energy.

Young ⁽⁴⁰⁾, performing experiments with simulated blast noise and other impulsive sounds, found that C and D2 weightings correlated best with the amalgamation of noises tested and that peak sound pressure level correlated the least.

The National Academy of Science ⁽³⁹⁾ concluded that peak amplitude is an inadequate descriptor of impulsive noise and that the C-weighted integrated energy offers the best measure to use at this time.

The consensus is that a frequency-weighted energy measure which goes down to low frequencies (5-30 Hz) is best for the assessment of human response to impulse noise and that a peak measure is inadequate.

3.2 When people respond indoors to a blast or boom stimulus, do they respond to the noise, to the noise-induced vibration, or both?

Kryter et al. ⁽²⁰⁾ measured wall vibration levels caused by sonic booms. The probable floor vibration levels corresponding to these wall vibrations were at levels found by Wiss and Parmelee ⁽²²⁾ to be just perceptible (much below annoying). In support of this conclusion, Kryter ⁽²¹⁾ found no change in the subjects' responses to the booms when they were isolated from vibration by placing their chairs on isolating mats.

Taylor et al. ⁽³⁸⁾ found vibration from subway operations and continuous impulsive sources to be barely or not at all perceptible, although residents complained of the vibration. They did, however,

find the secondary noise radiation from the walls, windows and bric-a-brac to be significant.

The early studies by Broadbent and Robinson⁽¹⁶⁾ and by Pearsons and Kryter⁽¹⁸⁾ which did not explicitly include room vibrations (and in the case of Broadbent and Robinson did not include adequate low frequency sound either) yielded essentially the same results as did later experiments by Johnson and Robinson⁽²³⁾ and by Kryter^(20,21,24,25) which did include room vibrations. That is, in all the experiments with subjects indoors, a sonic boom having a peak pressure of about 1.8-2.0 psf (outdoors) was found equivalent to an aircraft flyover having a maximum perceived noise level of about 109 dB (outdoors).

The evidence indicates that people indoors respond to the noise and the secondary noise produced by vibration. In the cases cited, the actual vibrations are barely or not at all perceptible although people hearing the noise radiated by the vibrating surfaces sometimes complain about "vibrations."

3.3 Can sonic boom data be used to infer response to open pit mining noise, and can blast data be used to infer response to sonic boom noise?

The answers to Question 1 suggest a frequency weighted energy measure be used to assess human response to impulse noise and that the very low frequencies which are below the house's natural vibration frequencies (below about 5-30 Hz) are unimportant.

The answers to question 2 suggest that house vibrations play

an important intermediate role in human response to blast noise. The data from Taylor⁽³⁸⁾ indicates that house vibrations are independent of source and occur at the natural frequencies of the house. Kryter's data⁽²⁰⁾ show the same type of wall vibrations as do Taylor's data. That is, houses respond at their natural frequencies to impulse stimuli. Thus, their response is related to the energy of the impulse at the natural frequencies of the house and largely independent of the shape (phase) of the impulse.

Fidell and Pearsons^(14,15) found the noisiness of impulse sounds to be dependent only on the magnitude of the noise spectrum and independent of phase. This means that a sonic boom or blast having the same spectrum and duration will be judged equally noisy, even though their wave forms may appear quite different.

Thus, people and houses respond to frequency weighted energy, and their response is independent of impulse shape. That is, people will respond in a similar manner to blasts or sonic booms having the same energy (above about 10 Hz) and duration. Since long sonic booms (bombers) and quarry blasts have similar energy above about 5 Hz and similar durations, human response data for one can be used to predict human response to the other. Smaller blasts are more similar to shorter booms such as those produced by fighter aircraft.

This comparability is further evidenced by the research of Webb and Warren⁽³⁰⁾ who used double explosive charges to simulate sonic booms and the research of Johnson and Robinson^(22,23) who used explosive charges, subsonic aircraft flyovers and sonic booms as sources.

They found the evaluation of the explosive charges to be consistent with, and similar to, the evaluation of the sonic booms.

Taylor et al.⁽³⁸⁾ state: "It can be concluded that from the points of view of damage and annoyance, the criteria derived from sonic boom studies may be reasonably applied to blast produced acoustic waves (quarry), although the effects of the latter may be a little more severe for the same overpressure."

The National Academy of Science⁽³⁹⁾ decided to use the sonic boom data base (i.e. Refs. 21, 33, 40 and others) to develop procedures for federal facilities to assess the impact of large amplitude impulse noise, including armor, artillery, demolition and open pit mining noise.

3.4 What characterizes people who complain about impulse noise?

The TRACOR study⁽³⁴⁾ and the Borsky study⁽³³⁾ both find that complainants have activities interfered with, are annoyed by the noise, usually own their own homes and feel that the impulse noise is damaging their property.

The large standard deviation in responses amongst subjects found by virtually every researcher in this area may have important implications when considering complaints. The large standard deviation may indicate that for levels of noise which are perfectly acceptable to the average person, there are substantially more complainants than for other types of noise, such as aircraft noise, for which there is relatively less variation in the responses of different people.

3.5 Is annoyance and are complaints related to the average impulse amplitudes and their frequency of occurrence, or to the fewer very loud impulses?

Borsky⁽³³⁾ at Oklahoma City found a direct monotonic relation between community reactions and average amplitude.

Webb and Warren⁽³⁰⁾ found a direct monotonic relation between community response and amplitude, and between community response and frequency of impulses.

de Brisson⁽³⁵⁾ found more negative reaction in areas of greater boom concentration.

The evidence indicates that annoyance reactions are proportional to the average impulse amplitudes and their frequency of occurrence.

On the other hand, Schomer⁽³⁶⁾ reports of complaints resulting from infrequent blasts. Possibly structure vibration and the resulting fear of damage to property generate complaints. These complaints seem to depend only on the amplitude of the blast reaching a threshold sufficient to shake the house, and not on frequency of occurrence or average amplitude.

3.6 Do people accommodate or grow used to impulse noise?

Kryter^(20,21), Nixon and Hubbard⁽³²⁾, Borsky⁽³³⁾, all indicate the possibility of a small accommodation to the noise, but none attempt to quantify it.

Webb and Warren⁽³⁰⁾ qualitatively indicate a finding of some accommodation to impulse noise.

3.7 For community response, what is more important: the response of people outdoors or indoors?

Only Johnson and Robinson⁽²²⁾ and Kryter^(20,21) have measured groups both outdoors and indoors in the same experiment. They both concluded that the indoor response, although it is more extreme, is the more important. Kryter's statement⁽²¹⁾ is typical.

"Although the effects of the sonic boom upon people outdoors are of considerable interest, the fact remains that people indoors object as much if not more to the effects of environmental noise, even though the noise itself is generated outdoors and even though the house or building structure attenuates and reduces somewhat the intensity of the sound. This is usually attributed to the fact that people indoors demand and have a greater need for protection against noise because their indoor activities differ from the outdoor activities and because they spend more time indoors.

In the case of the sonic boom it is possible that the sonic boom and the house will interact in such a way that the interference effects on humans are augmented more than are other externally generated sounds, the reason being that components of the house structure are driven beyond their usual response and make the house "rattle," "creak," etc. In any event, it seems likely that the effects of sonic booms on people indoors will strongly determine acceptability to people of the sonic booms."

Kryter^(20,21) and Schomer⁽⁴¹⁾ both make the point that the normal home attenuates the blast noise and sonic boom far less than it does normal noises such as road traffic or aircraft noise. Thus, people being accustomed to a certain degree of protection from their dwelling, will find sonic boom and blast noise relatively more annoying indoors

than out-of-doors, because while indoors they will perceive the originating outdoor noise to be louder than it actually is.

3.8 Are there any adverse physiological effects expected from open-pit mining noise at the levels normally encountered in the community?

Nixon and Hubbard⁽³²⁾ concluded from the tests in the St. Louis area that "there were no direct adverse physiological effects."

Nixon et al.⁽⁴⁷⁾ found no physiological effects on people subjected to booms with peak amplitudes up to 144 psf.

3.9 Does open-pit mining noise have an effect on livestock?

Kryter⁽²⁰⁾ found at Edwards Air Force Base no significant response in the animals. Only avian species showed any response, and their response was more pronounced to low flying subsonic aircraft than to booms. The researchers pointed out that these tests were limited and cannot be considered conclusive, and that the animals were preconditioned to 4 to 8 sonic booms per day.

Nixon et al.⁽⁴⁷⁾ found no observable reaction in livestock to high level booms (50 to 144 psf). They also pointed out that their tests were limited in nature and that the animals were preconditioned to hearing booms.

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APPENDIX A
GLOSSARY OF TERMS

This glossary contains definitions for terms and/or figures for wave forms. Citation numbers in parentheses correspond to listings in ANSI-S1.1-1960, Acoustical Terminology, issued by the American National Standards Institute.

1. Ambient noise (1.25). Ambient noise is the all-encompassing noise associated with a given environment, being usually a composite of sounds from many sources near and far.
2. Amplitude. The magnitude of the departure of a signal, such as pressure, from its ambient or static value.
3. Bel (2.2). The bel is a unit of level when the base of the logarithm is 10. Use of the bel is restricted to levels of quantities proportional to power.
4. Decibel (2.3). The decibel is one tenth of a bel. Thus, the decibel is a unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power.

NOTE 1: Examples of quantities that qualify are power (any form), sound pressure squared, particle velocity squared, sound intensity, sound-energy density, voltage squared. Thus the decibel is a unit of sound pressure-squared level; it is common practice, however, to shorten this to sound pressure level because ordinarily no ambiguity results from so doing.

NOTE 2: The logarithm to the base the tenth root of 10 is the same as ten times the logarithm to the base 10: e.g., for a number X^2 , $\log_{10^{1/10}} X^2 = 10 \log_{10} X^2 = 20 \log_{10} X$. This last relationship is the one ordinarily used to simplify the language in definitions of sound pressure level, etc.

5. Blast wave form. The graphical shape of the variation in amplitude of air pressure as a function of time. See also "ideal blast wave form".
6. Double explosion. A pair of small explosive charges (about 5 lbs. of explosives each) used to simulate a sonic boom and detonated sequentially about 0.1 to 0.5 seconds apart or separated spatially to achieve the same time delay.
7. Doublet (Figure A1). A pair of ideal impulses (delta-functions), one positive and one negative, separated by an arbitrary time T (usually a short time).
8. Duration. The time in seconds between the instant that an impulse first rises above the ambient and the instant that it last recedes below the ambient.
9. Effective sound pressure (1.50). The effective sound pressure at a point is the root-mean-square value of the instantaneous sound pressures, over a time interval at the point under consideration. In the case of periodic sound pressures, the interval must be an integral number of periods or an interval that is long compared to a period. In the case of nonperiodic sound pressures, the interval should be long enough to make the value obtained essentially independent of small changes in the length of the interval.

NOTE: The term "effective sound pressure" is frequently shortened to "sound pressure."

10. EPNL - Effective perceived noise level in EPNdB. The sum as calculated by formulas given of PNdb, in successive .5-sec intervals during the occurrence of a sound, minus 15 plus a correction for time. The sum of these calculations is called

EPNdB. The value -13 comes from the choice of 20 one-half second intervals (a duration of 10 sec) as a standard duration to which all effective levels are referred.

11. Energy. As used in this report, energy means a quantity proportional to the integral over all time of the square of the instantaneous signal amplitude.
12. Frequency (1.9). The frequency of a function periodic in time is the reciprocal of the primitive period. The unit is the cycle per unit time and must be specified.

[NOTE: The cycle per second is now called the Hertz (Hz).]

13. Frequency domain. The mathematical domain in which time varying signals are described in terms of their spectral content. For linear systems, the time and frequency domains form a unique pair related by the Laplace transform.
14. Guttman Scale. Social scientists, particularly those engaged in psychological and attitudinal research, have developed a large number of techniques for combining individual items into scales and indexes.

One of these techniques, scalogram analysis, commonly termed Guttman scaling after its originator, has become widely used in many types of social science research, particularly in the area of attitude measurement in survey research.

Guttman scale analysis is a means of analyzing the underlying operating characteristics of three or more items in order to determine if their interrelationships meet several special properties which define a Guttman scale. Guttman

scales must first be unidimensional, that is, the component items must all measure movement towards or away from the same single underlying object. The substance of the object is unimportant; it may be racial prejudice, sense of political efficacy, or even the technological development of societies. Similarly, the unit of analysis may be individuals, nations, etc.

Second, Guttman scales must be cumulative, and it is this property which differentiates Guttman scales from almost all other types of scales and indexes. Operationally, a cumulative scale implies that the component items can be ordered by degree of difficulty and that respondents who reply positively to a difficult item will always respond positively to less difficult items and vice versa.

15. Ideal blast wave form (Figure A2). This wave form represents an ideal blast near to the explosion.
16. Ideal N-wave (Figure A3). This wave form represents an ideal sonic boom. Due to wave steepening, blast wave forms take on this shape at moderate distances (dependent on charge size) from the explosion. (See also "N-wave".)
17. Intensity. In this report, intensity means a quantity proportional to the square of a simply measurable parameter such as pressure or velocity.
18. Level (2.1). In acoustics, the level of a quantity is the logarithm of the ratio of that quantity to a reference quantity of the same kind. The base of the logarithm, the reference

quantity, and the kind of level must be specified.

NOTE 1: Examples of kinds of levels in common use are electric power level, sound-pressure-squared level, voltage-squared level.

NOTE 2: The level as here defined is measured in units of the logarithm of a reference ratio that is equal to the base of logarithms.

NOTE 3: In symbols,

$$L = \log_r (q/q_0)$$

where

L = level of kind determined by the kind of quantity under consideration, measured in units of $\log_r$

r = base of logarithms and the reference ratio

q = the quantity under consideration

q_0 = reference quantity of the same kind

NOTE 4: Differences in the levels of two like quantities q_1 and q_2 are described by the same formula because, by the rules of logarithms, the reference quantity is automatically divided out:

$$\log_r (q_1/q_0) - \log_r (q_2/q_0) = \log_r (q_1/q_2)$$

19. NEF - Noise Exposure Forecast. A community average noise measure based upon the logarithmic sum of the EPNL of events during a typical day, including a penalty for events at night and an arbitrary scale constant.
20. N-wave (Figure A3). An N-wave is a transient pressure signature in the form of an N. It is characterized by a fast compression, a slow decay into a rarified state, and a sharp return to ambient pressure. See also "ideal N-wave".
21. Noy. The unit of perceived noisiness is called the "Noy." Noy values, as the result of judgment tests conducted in the laboratory, have been assigned to the SPL of bands of frequencies present during an interval of .3 sec.

- 22. 1/2 N-wave. The first or positive half of an N-wave.
- 23. 1 msec rise N-wave (Figure A4). An N-wave for which the abrupt transitions take 1 msec to occur rather than occurring instantaneously as in the ideal N-wave.
- 24. Overpressure. The overpressure is the maximum instantaneous pressure that occurs during the interval of an impulse. In this report, the decibel equivalent of the overpressure re 20 μ Pa is identical to the "peak level" or "peak sound pressure level."
- 25. Peak Level (2.12). The peak level is the maximum instantaneous level that occurs during a specified time interval. In acoustics, peak sound pressure level is to be understood, unless some other kind of level is specified.
- 26. Peak Sound Pressure. The peak sound pressure for any specified time interval is the maximum absolute value of the instantaneous sound pressure in that interval.

NOTE: In the case of a periodic wave, if the time interval considered is a complete period, the peak sound pressure becomes identical with the maximum sound pressure.

- 27. Peaked 1/2 N-wave. (Figure A5).
- 28. Periodic Quantity (1.6). A periodic quantity is an oscillating quantity whose values recur for certain increments of the independent variable.

NOTE 1: If a periodic quantity v is a function of t , then

$$v = f(t) = f(t + T)$$

where T , a constant, is a period of v .

NOTE 2: In general, a periodic function can be expanded into a series of the form

$$y = f(t) = A_0 + A_1 \sin(\omega t + a_1) + A_2 \sin(2\omega t + a_2) + \dots,$$

where

ω , a positive constant, equals 2π divided by the period T , and the A 's and a 's are constants which may be positive, negative, or zero.

29. Phase of a Periodic Quantity (1.18). The phase of a periodic quantity, for a particular value of the independent variable, is the fractional part of a period through which the independent variable has advanced, measured from an arbitrary reference.

NOTE: The arbitrary reference is generally so chosen that the fraction is less than unity. In case of a simply harmonic quantity, the reference is often taken as the last previous passage through zero from the negative to positive direction.

30. PNdB. The perceived noise level (PNL) expressed in dB.
31. PNL. Perceived Noise Level. The sum, as calculated according to prescribed procedures, of the noy values of a frequency band or frequency bands of sound is designated as Perceived Noise Level in PNdB.
32. psf - the instantaneous pressure expressed in pounds per square foot.
33. Rise time. The rise time with respect to an impulse is the duration of the transition from ambient pressure to peak instantaneous pressure.
34. Root-mean-square sound pressure - see effective sound pressure.
35. SEL. The sound exposure level (SEL) is the integral over all time of the square of the instantaneous sound pressure.

36. Sound (1.1).

(1) Sound is an oscillation in pressure, stress, particle displacement, particle velocity, etc., in a medium with internal forces (e.g., elastic, viscous), or the superposition of such propagated oscillations.

(2) Sound is an auditory sensation evoked by the oscillation described above.

NOTE 1: In case of possible confusion, the term "sound wave" or "elastic wave" may be used for concept (1) and the term "sound sensation" for concept (2). Not all sound waves can evoke an auditory sensation; e.g., ultrasound.

NOTE 2: The medium in which the sound exists is often indicated by an appropriate adjective; e.g., air-borne, water-borne, structure-borne.

37. Sound Pressure (1.47). The sound pressure at a point is the total instantaneous pressure at that point in the presence of a sound wave minus the static pressure at that point.

38. Sound Pressure Level (2.6). The sound pressure level, in decibels, of a sound is 20 times the logarithm to the base 10 of the ratio of the pressure of this sound to the reference pressure. The reference pressure shall be explicitly stated.

NOTE 1: The following reference pressures are in common use:

(a) 20 micropascal (b) 1 microbar

Reference pressure (a) is in general use for measurements concerned with hearing and with sound in air and liquids, while (b) has gained widespread acceptance of calibration of transducers and various kinds of sound measurements in liquids.

NOTE 2: Unless otherwise explicitly stated, it is to be understood that the sound pressure is the effective (rms) sound pressure.

NOTE 3: It is to be noted that in many sound fields the sound pressure ratios are not the square roots of the corresponding power ratios.

39. Spectrum (1.34).

(1) The spectrum of a function of time is a description of its resolution into components, each of different frequency and (usually) different amplitude and phase.

(2) "Spectrum" is also used to signify a continuous range of components, usually wide in extent, within which waves have some specified common characteristic; e.g., "audio-frequency spectrum."

NOTE: The term "spectrum" is also applied to functions of variables other than time, such as distance.

40. Spectrum Level (Spectrum Density Level). (2.8). The spectrum level of a specified signal at a particular frequency is the level of that part of the signal contained within a band 1 hertz wide, centered at the particular frequency.

Ordinarily this has significance only for a signal having a continuous distribution of components within the frequency range under consideration. The words "spectrum level" cannot be used alone but must appear in combination with a prefatory modifier; e.g., pressure, velocity, voltage.

NOTE: For illustration, if L_p be a desired pressure spectrum level, p the effective pressure measured through the filter system, p_0 reference sound pressure, Δf the effective bandwidth of the filter system (see 7.27), and $\Delta_0 f$ the reference bandwidth (1 hertz), then

$$L_{ps} = 10 \log_{10} \left[\frac{p^2 / \Delta f}{p_0^2 / \Delta_0 f} \right]$$

For computational purposes, if L_p is the band pressure level observed through the filter, the above relation reduces to

$$L_{ps} = L_p - 10 \log_{10} \frac{\Delta f}{\Delta_0 f}$$

41. Square Law. See effective sound pressure.
42. Square Wave (Figure A6).
43. Static Pressure (1.45). The static pressure at a point is the pressure that would exist at that point in the absence of sound waves.
44. Super Boom (Figure 47). A received sonic boom for which the energy has been focused at a point on the ground because of manoeuvres of the aircraft (typically climbs or dives). The wave form is similar to a blast.
45. Time Domain. The mathematical domain in which time varying signals are described in terms of their shape as a function of time. For linear systems, the time and frequency domains form a unique pair related by the La Place transform.
46. Triangle Wave. (Figure A1).
47. Wave (1.19). A wave is a disturbance which is propagated in a medium in such a manner that at any point in the medium the quantity serving as measure of disturbance is a function of the time, while at any instant the displacement at a point is a function of the position of the point.

Any physical quantity that has the same relationship to some independent variable (usually time) that a propagated disturbance has, at a particular instant, with respect to space, may be called a wave.

48. White Noise (1.28). White noise is a noise whose spectrum density (or spectrum level) is substantially independent of frequency over a specific range.

NOTE: White noise need not be random.

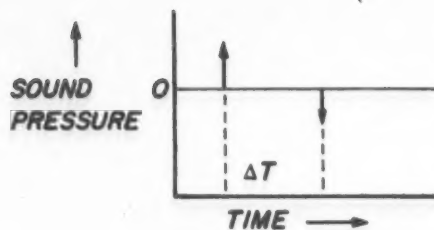


FIGURE A1 DOUBLET WAVE

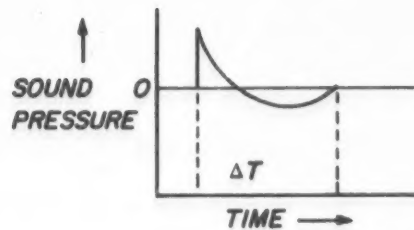


FIGURE A2 IDEAL BLAST WAVE

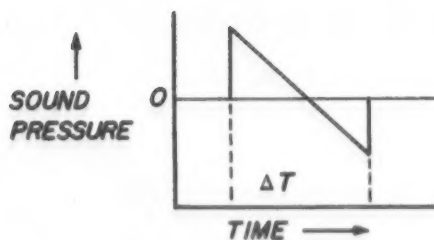


FIGURE A3 IDEAL N-WAVE

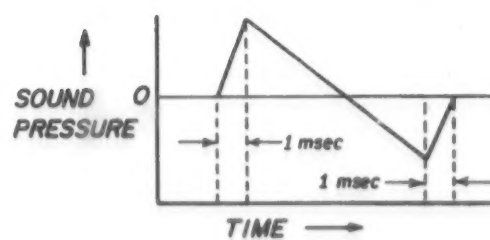


FIGURE A4 1 MSEC RISE TIME N-WAVE

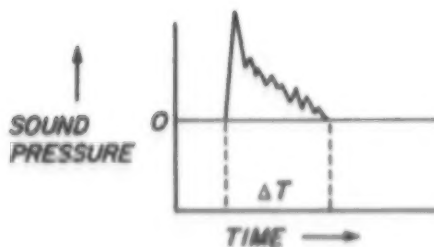


FIGURE A5 PEAKED HALF N-WAVE

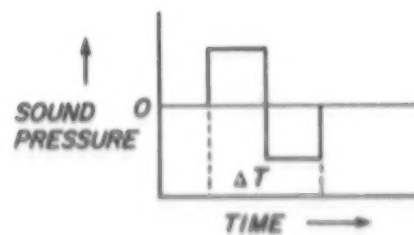


FIGURE A6 SQUARE WAVE

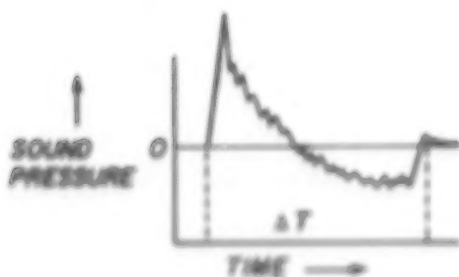


FIGURE A7 SUPER BOOM WAVE

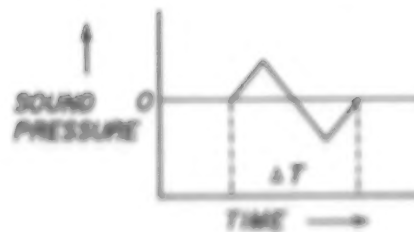


FIGURE A8 TRIANGLE WAVE

APPENDIX B

Authors Name, Page(s) Where Reference is Discussed
and Reference Number

1.	Boone, M. M.	13 (11)
2.	Borsky, P. N.	45 (33, 45)
3.	Broadbent, D. E. and Robinson, D. W.	16 (16)
4.	Carter, N. L.	14 (13)
5.	Committee on Hearing, Bioacoustics and Biomechanics	58 (39)
6.	de Brisson, M.	53 (35)
7.	Fidell, S. and Pearsons, K. S.	14 (14)
8.	Fidell, S. et al.	14 (15)
9.	Garner, W. R.	9 (2)
10.	Garrett, R. M.	11 (8)
11.	Gustafsson, B.	14 (12)
12.	Johnson, D. R. and Robinson, D. W.	36 (22, 23)
13.	Kryter, K. D.	54, 62 (37, 44)
14.	Kryter, K. D. and Lukas, J. S.	41 (25)
15.	Kryter, K. D. et al.	24 (20, 21)
16.	Lukas, J. S. and Dobbs, M. E.	41 (28)
17.	Lukas, J.S. and Kryter, K. D.	39, 41 (24, 26)
18.	Lukas, J. S. et al.	41 (27)
19.	Miller, G. A.	10 (3)
20.	Munson, W. A.	9 (4)
21.	Nixon, C. W. and Hubbard, H. H.	44 (32)

22.	Nixon, C. W. et al.	62 (47)
23.	Pearsons, K. S. and Kryter, K. D.	23 (18)
24.	Reichardt, W.	13 (10)
25.	Reichardt, W. and Niese, J.	12 (9)
26.	Rylander, R. et al.	43 (31)
27.	Schomer, P. D.	54, 61 (36, 41)
28.	Shepard, L. J. and Sutherland, W. W.	21 (19)
29.	Sutherland, L. S. et al.	62 (46)
30.	Taylor, A. G., et al.	55 (38)
31.	TRACOR, Inc.	51 (34)
32.	von Bekeasy, G.	9 (1)
33.	von Gierke, H. E.	62 (42)
34.	von Gierke, H. E. and Nixon, C. W.	62 (43)
35.	von Niese, H.	10 (6)
36.	von Port, E.	10 (5)
37.	von Zwicker, E.	10 (7)
38.	Webb, D. R. B. and Warren, C. H. E.	42 (30)
39.	Wiss, J. F. and Parmelee, R. A.	36, 58 (29)
40.	Young, J. R.	59 (40)
41.	Zeppler, E. E. and Harel, J. R. P.	18 (17)

APPENDIX C

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Evaluation of C-weighted L_{dn} for assessment of impulse noise

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(Received 17 January 1977; revised 22 April 1977)

Community response to impulsive noise, such as sonic boom, artillery fire, and other military ordinance, and quarry and mining operations, is currently a matter of great public interest. Recently, the EPA has proposed the use of the C-weighted day-night level to estimate community response to large amplitude single-event impulsive noise. This measurement and its associated exposure criteria have been derived largely on the basis of existing community response to sonic boom data. Recent laboratory measurements of human reaction to artillery-type noise, reported on herein, strongly support this C-weighted measure.

PACS numbers: 43.50.Ba, 43.50.Qp, 43.50.Sr

INTRODUCTION

The EPA has proposed an interim impulsive noise measure in addition to the day-night average sound level (DNL) which has been specified as the primary descriptor for environmental noise on the basis of the perception by people of audible sound.¹ Basically, this new measure yields a C-weighted DNL for single event large amplitude impulsive noises, where large amplitude is defined to mean events having a C-weighted sound exposure level [SEL-defined in Eq. (1) below] in the excess of 85 dB during daytime hours (7 a.m. - 10 p.m.), and a C-weighted SEL in excess of 75 dB during nighttime hours (10 p.m. - 7 a.m.). Appendix A describes the C-weighted measure.

Large amplitude impulsive sounds, such as those produced by sonic boom, quarry blasts or artillery fire can excite noticeable vibration of buildings and other structures.^{2,3} These induced vibrations may generate additional annoyance to people beyond that due to audibility of the impulse because of "house rattling" and "startle," as well as additional contributions to interference with speech or sleep.^{4,5} These large amplitude, structure shaking sources are contrasted with small size (small SEL) impulsive sources such as rifle fire, toy "cap" pistols, etc.

In the past, it has been general practice to describe large-amplitude impulsive sounds in terms of the peak sound pressure in a wide-frequency band (e.g., quarry operations, sonic boom). Peak pressure may be satisfactory for description of impulses having a restricted range of peak pressures and durations. It is not sufficient as a general description for use in measurement or prediction of the combined environmental effects of impulses having substantially different pressure versus time characteristics since the energy coupled into a structure is dependent on the spectral content of the impulse. Moreover, use of peak pressure can be unwieldy when a succession of impulses, sometimes overlapping, must be evaluated.

The C-weighted average sound level was chosen as a suitable descriptor because it provides the basis of a procedure that relates to the sound-induced vibrations in buildings. Criteria were established by equating the percent of population highly annoyed to sonic boom at

various C-weighted levels to the population highly annoyed to more normal noises (primarily aircraft and traffic noise survey data) at various A-weighted L_{dn} levels. The Edwards Air Force Base⁶ and Oklahoma City⁷ studies were primary bases for this procedure for large impulsive sounds.

In the Oklahoma City study, the population was questioned if they were annoyed, and if so, if they were very annoyed, moderately annoyed or little annoyed. The percent very annoyed was chosen as best matching the highly annoyed described in the EPA levels document.⁸ Analysis of the data showed that approximately the same percentage of the population was highly annoyed in an environment having an impulsive C-weighted L_{dn} level of 60 dB as was a population in an area with an A-weighted L_{dn} of 60 dB.

Because of the equivalency of the two measures on a percent highly annoyed basis, DNL for impulse noise is derived from the individual CSEL's and called C-weighted day-night average sound level. Further, assessment of the overall noise environment, combining the effects of impulsive sounds described by CDNL, is made in terms of a composite day-night average sound level. The contribution of the impulses, in terms of CDNL (C-weighted), is added, logarithmically, to the DNL (A-weighted) of other sources to obtain the composite DNL for the combination.⁹

I. PURPOSE

The purpose of this paper is to report on the analysis of new laboratory tests of subjective response to simulated blast sounds. It is important to note that these are laboratory tests in contrast to the survey test data used to initially derive the above C-weighted procedure.

II. THE NEW DATA

The psychological annoyance of simulated explosion sequences have been studied at the Stanford Research Institute.¹⁰ In this study, a special testing room, originally designed for human response to sonic boom research, was modified to create artillery type sounds.¹¹ In a quasirandom sequence, subjects judged the annoyance of various artillery type sounds (different amplitudes, durations, etc.) in relation to recorded aircraft

TABLE 1. Summary of physical and psychological data for stimuli used in the psychoacoustic experiment.

Noises	Physical measures ^a				Mean magnitude estimates of annoyance	
	Peak SPL	SEL-A	SEL-C	SEL-D2	$\bar{M}_r$	$\log_{10} \bar{M}_r$
Blasts	85.25	57.25	78.00	65.50	2.4	0.3803
	90.00	62.25	81.50	70.00	3.6	0.5583
	100.75	74.75	93.75	83.50	22.8	1.358
	107.25	74.75	93.50	82.25	26.7	1.427
	102.75	73.50	90.75	80.75	20.0	1.301
	111.75	77.75	96.75	85.75	34.4	1.537
	112.50	81.75	99.75	89.00	41.9	1.622
	119.25	86.50	104.75	94.25	62.6	1.797
Glass breaking	100.25	78.25	80.75	81.75	10.7	1.075
	104.75	85.25	87.25	87.00	13.1	1.117
	105.00	80.00	83.25	83.50	17.5	1.243
	107.75	87.25	90.25	89.75	16.0	1.204
Horn (short)	106.50	92.00	91.75	90.50	53.1	1.728
Horn (long)	104.75	93.50	93.25	100.25	62.9	1.799
747 Take off	70.00	58.25	64.75	62.75	3.4	0.5314
	80.00	65.25	74.75	73.75	8.2	0.7924
	90.00	78.25	84.75	82.75	10.0 ^b	1.000
	100.00	89.25	94.75	92.75	26.2	1.418
DC-8 (landing)	110.00	90.25	104.75	102.75	49.1	1.691
DC-8 (taxiing)	70.00	57.25	64.25	65.75	2.9	0.4625
	80.00	67.25	74.25	75.75	5.9	0.7709
	90.00	77.25	84.25	85.75	11.0	1.041
	100.00	87.25	94.25	95.75	29.9	1.476
	110.00	97.25	104.25	105.75	55.5	1.744

^aPhysical data values are rounded to nearest 1 dB.^bReference noise with assigned annoyance value of 10.

fly-over sounds, breaking glass sounds and airhorn sounds. The subjects used magnitude estimation procedures to assign annoyance values to the various noise stimuli presented. One of the aircraft fly-over sounds was the reference value and was assigned a magnitude of 10.

The aircraft fly-overs were filtered to have a spectral content and level as normally recorded indoors, the artillery sounds and their associated room vibrations were made to be similar to actual indoor recordings, the glass breaking was an indoor sound and the air horn was "filtered" by the double wall of the test room.

Thirty adult subjects, 18 female and 12 male, hired in the Stanford area, were used for the test. The geometric mean of their magnitude estimates was used as the overall estimate of annoyance for each of the various stimuli. These overall estimates of annoyance were plotted against and compared to four physical measures: peak sound pressure level, A-weighted SEL, C-weighted SEL and D2-weighted SEL. Table I summarizes these data; the terms used in this table are defined as follows:

Peak SPL—The peak value achieved by the time-varying sound pressure during the occurrence of a noise.

ASEL, CSEL and D2SEL—Sound exposure levels calculated from A-, C-, or D2-weighted sound pressures, respectively.

Sound exposure levels are computed as

$$SEL = 10 \log \left[\frac{1}{p_0^2 t_0} \int_0^T \hat{p}^2(t) dt \right], \quad (1)$$

where $\hat{p}(t)$ is a time-varying sound pressure weighted by a prescribed frequency-dependent weighting network, such as A, C, or D2.

p_0 is the reference pressure of 20 μ Pa, and t_0 equals 1 s.

III. ANALYSIS OF THE DATA

In order to compare the validity of equating impulsive C-weighted L_{dn} to A-weighted L_{dn} , it is first necessary to establish a correction factor for the impulsive noise since buildings will attenuate aircraft noise more than they will attenuate the low-frequency impulsive noise. That is, an aircraft fly-over having an A-weighted SEL of 80 dB indoors might have an outdoor A-weighted SEL of 95 or 100 dB (the building attenuates 15–20 dB on average). In contrast, a low-frequency, large-amplitude blast noise or sonic boom having a C-weighted SEL indoors of 85 dB might have an outdoor C-weighted SEL of 90–95 dB because the building attenuation is less to the lower-frequency impulse spectra than it is to the higher frequency aircraft spectra. A few measurements

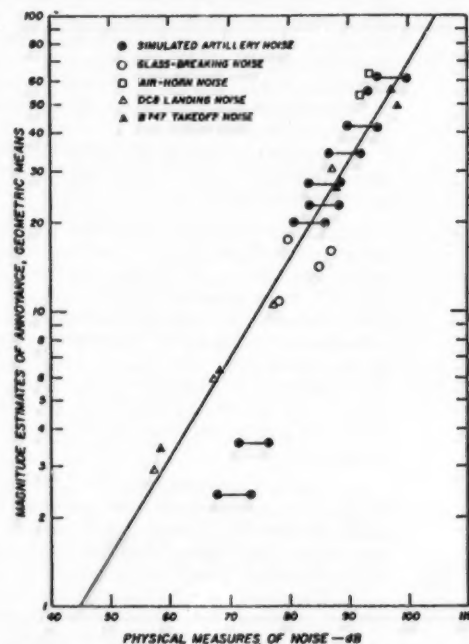


FIG. 1. Relationship between psychological annoyance and physical stimuli values. All stimuli are A-weighted SEL's (indoors) except the artillery noise which is C-weighted and corrected as explained in the text to account for the reduced building attenuation to low-frequency impulsive noises as compared with the building attenuation to aircraft or airhorn spectra. The solid line is a least-square fit to the nonartillery noises.

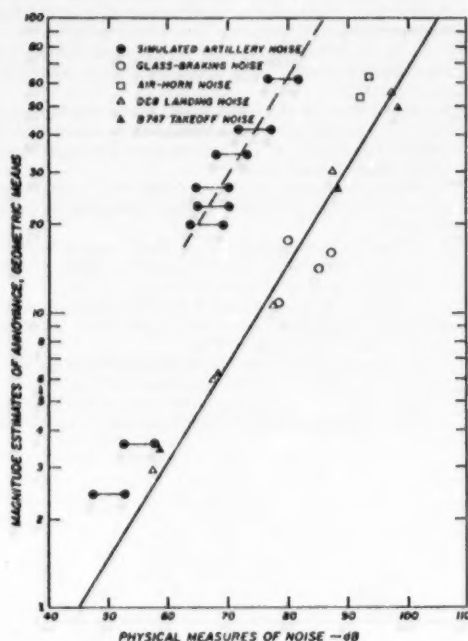


FIG. 2. Relationship between psychological annoyance and physical stimuli values. All stimuli are A-weighted SEL's (indoors) except the artillery noise which is A-weighted and corrected as explained in the text to account for the reduced building attenuation to low frequency impulsive noises as compared with the building attenuation to aircraft or airhorn spectra. The solid line is a least squares fit to the nonartillery noises and the dashed line is approximately fit to the six larger blast noises but constrained to be parallel to the solid line.

by the Construction Engineering Research Laboratory indicate that typical building attenuation for large amplitude impulsive noises is on the order of 5-8 dB¹² and recent measurements by Kamperman give a 4-dB attenuation figure for quarry blasts.³ Thus, to properly test the equivalence of the outdoor criteria by comparing the indoor A-weighted aircraft, breaking glass and air horn sounds to the indoor C-weighted impulse, it is first necessary to add 5-10 dB to the C-weighted indoor impulsive noise SEL's.

Figure 1 compares "outdoor" A-weighted SEL's for the aircraft, the glass breaking and the air horn to the range of C-weighted SEL's for the blast sounds. As explained above, 5 to 10 dB are added to these blast sound SEL's in order to correctly perform this "outdoor" comparison. The line on the figure is a least squares fit to the A-weighted data.

By way of comparison, Fig. 2 presents the same A-weighted aircraft, glass breaking and air horn sounds along with the A-weighted blast data corrected by 5 to 10 dB. As can be seen, a line fit to six larger blast noise sounds is displaced 15-20 dB from the line fit to the other A-weighted sounds.

IV. CONCLUSIONS

Figure 1 implies a close comparison between the A-weighted $L_{A\pi}$ measure used out-of-doors for typical sounds and the C-weighted impulse criteria applied out-of-doors. It is also evident from Fig. 1 that when the C-weighted SEL for an impulse is less than about 85 dB, the impulse curve begins to drop below the A-weighted curve and, thus, should not be used. (The EPA procedure cuts off at a C-weighted SEL of 85 dB.) Thus, it is felt that these data offer a very good verification for the EPA's interim C-weighted impulsive noise measure.

In contrast, Fig. 2 shows that A-weighting greatly underestimates blast noise annoyance in the absence of a large correction factor.

APPENDIX: EVALUATION OF LARGE AMPLITUDE IMPULSES¹³

A. Large amplitude impulses

A large-amplitude impulse is an event in which the C-weighted sound exposure level, CSEL, is greater than 85 dB in daytime and 75 dB at night. Also, the maximum C-weighted Sound Exposure Level resulting from the event in a single 2-s time period shall be 10 dB greater than the C-weighted Sound Exposure Level resulting from any other 2-s period of the event.

Note: An approximate evaluation of the threshold requirements acceptable for this procedure may be made with a standard sound-level meter, meeting the Type I characteristics of ANSI S1.2-1971, employing C-weighting and "slow" meter characteristic. In order for the impulse to be considered in this procedure it should produce a maximum meter reading in excess of 82 dB in daytime and 72 dB at night.

B. C-weighted sound exposure level—CSEL

The mathematical description of C-weighted sound exposure level in decibels is

$$CSEL = 10 \log \left[\frac{1}{t_0} \int_{-\infty}^{\infty} \frac{p_c^2}{p_0^2} dt \right], \quad (1)$$

where $t_0 = 1$ s, p_c = C-weighted sound pressure, and $p_0 = 20 \mu\text{Pa}$.

Note: In practice the integral is often approximated by integration within the time during which the sound level of the event exceeds a threshold value such as 20 dB less than the maximum sound pressure level.

C. C-weighted day-night average sound level - L_{Cdn}

Analogous to the A-weighted DNL, $L_{A\pi}$, with a nighttime penalty of 10 dB the C-weighted day-night average sound level is

$$L_{Cdn} = 10 \log(1/T_0) [15 \times 10^{L_{Cd}/10} + 9 \times 10^{(L_{Cn}+10)/10}], \quad (2)$$

where T_0 is 24 hours, L_{Cd} is the average C-weighted sound level over the daytime period of 0700 to 2200 h, L_{Cn} is the C-weighted average level over the nighttime period of 2200 to 0700 h.

Note: The C-weighted average level is most easily calculated from the C-weighted sound exposure levels during the time of interest as follows:

$$L_{Ct} = 10 \log \frac{1}{15 \times 3600} \left[\sum_i 10^{L_{Ct_i}/10} \right], \quad (3)$$

$$L_{Ca} = 10 \log \frac{1}{9 \times 3600} \left[\sum_i 10^{L_{Ct_i}/10} \right], \quad (4)$$

where L_{Ct_i} is the C-weighted sound exposure level of the i th discrete event.

¹Letter from Mr. C. L. Elkins, Environmental Protection Agency, to Mr. P. J. Fliakas, Assistant Secretary of Defense, dated 29 March 1976.

²John A. Blume *et al.*, "Sonic Boom Experiments at Edwards AFB, Annex G, Response of Structures to Sonic Booms," Interim Report, Stanford Research Institute, (28 July 1967).

³George W. Kamperman and Mary A. Nicholson, "The Transfer Function of Quarry Blast Noise and Vibration into Typical Residential Structures," Draft Final Report prepared for the EPA (December 1976) (unpublished).

⁴P. N. Borsky, "Community Reactions to Sonic Booms in the

Oklahoma City Area," National Opinion Center, AMRL-TR-65-37 (1965).

⁵K. D. Kryter, P. L. Johnson, and J. R. Young, "Psychological Experiments on Sonic Booms Conducted at Edwards AFB," Final Report, Stanford Research Institute ETU-6065 (1968).

⁶Reference 5.

⁷P. N. Borsky, "Community Reactions to Sonic Booms in the Oklahoma City Area," National Opinion Center, AMRL-TR-65-37 (1965).

⁸"Information Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," Appendix D, U. S. Environmental Protection Agency 550/9-74-004 (March 1974).

⁹"Guidelines for Preparing Environmental Impact Statements on Noise," Report of CHABA Working Group No. 69 (February 1977).

¹⁰J. R. Young, "Measurement of the Psychological Annoyance of Simulated Explosion Sequences" (Second Year). Stanford Research Institute (February 1976).

¹¹J. R. Young, "Measurement of the Psychological Annoyance of Simulated Explosion Sequences" (First Year). Stanford Research Institute (January 1975).

¹²Measurements by the Construction Engineering Research Laboratory Staff at Fort Sill, Lawton, OK (Spring 1974).

¹³"Guidelines for Preparing Environmental Impact Statements on Noise," Report of CHABA Working Group No. 69 (February 1977).